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UNCERTAINTY IN EXPOSURE
OF UNDERGROUND MINERS
TO RADON DAUGHTERS AND THE EFFECT OF
UNCERTAINTY ON RISK ESTIMATES

by

SENEC Consultants Limited

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A report prepared by SENEZ Consultants Limited under contract to
the Atomic Energy Control Board

ABSTRACT

Studies of underground miners provide the principal basis for assessing the risk from radon daughter exposure. An important problem in all epidemiological studies of underground miners is the reliability of the estimates of the miners' exposures. This study examines the various sources of uncertainty in exposure estimation for the principal epidemiologic studies reported in the literature including the temporal and spatial variability of radon sources and, with the passage of time, changes to both mining methods and ventilation conditions. Uncertainties about work histories and the role of other hard rock mining experience are also discussed.

The report also describes two statistical approaches, both based on Bayesian methods, by which the effects on the estimated risk coefficient of uncertainty in exposure (WLM) can be examined. One approach requires only an estimate of the cumulative WLM exposure of a group of miners, an estimate of the number of (excess) lung cancers potentially attributable to that exposure, and a specification of the uncertainty about the cumulative exposure of the group. The second approach is based on a linear regression model which incorporates errors (uncertainty) in the independent variable (WLM) and allows the dependent variable (cases) to be Poisson distributed. The method permits the calculation of marginal probability distributions for either slope (risk coefficient) or intercept. The regression model approach is applied to several published data sets from epidemiological studies of miners. Specific results are provided for each data set and apparent differences in risk coefficients are discussed. The studies of U.S. uranium miners, Ontario uranium miners and Czechoslovakian uranium miners are argued to provide the best basis for risk estimation at this time.

In general terms, none of the analyses performed are inconsistent with a linear exposure-effect relation. Based on analyses of the overall miner groups, the most likely ranges for the absolute and relative risk coefficients are from less than 5 to about 15 cases per million person-years per WLM and from less than 0.5% to about 1.5% per WLM, respectively.

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RÉSUMÉ

Les études épidémiologiques sur les mineurs souterrains constituent la principale source d'information dans l'évaluation du risque d'exposition aux produits de filiation du radon, mais l'incertitude des estimations des expositions est l'un des problèmes importants de toute étude de ce genre. La présente étude analyse les différentes sources d'incertitude dans les principales études épidémiologiques publiées. Ces incertitudes incluent les variations temporelles et spatiales des sources de radon, ainsi que les changements entraînés par l'évolution des méthodes d'exploitation minière et des conditions d'aérage. Finalement, le rapport traite des incertitudes entourant les expériences de travail antérieures et l'influence des emplois passés dans d'autres mines de métaux.

Le rapport décrit aussi deux approches statistiques, toutes deux basées sur la méthode de Bayes qui permet d'examiner l'estimation du coefficient de risque dû à l'incertitude des expositions en unités alpha-mois (WLM). Une de ces approches requiert l'exposition cumulée d'un groupe de mineurs, l'estimation du nombre supplémentaire de cas de cancer du poumon qui peuvent être attribuables à cette même exposition, ainsi que l'évaluation de l'incertitude des expositions cumulées du groupe. La seconde approche est basée sur un modèle de régression linéaire qui comprend les erreurs (incertitude) sur la variable indépendante (WLM) et suppose une distribution de Poisson de la variable dépendante (cas). Cette méthode permet de calculer la distribution de probabilités marginales pour la pente (coefficient de risque) ou pour l'intersection avec l'axe vertical. L'approche du modèle de régression est appliquée à plusieurs ensembles de données provenant d'études épidémiologiques de mineurs. Certains résultats particuliers sont présentés pour chaque ensemble de données et les changements évidents du coefficient de risque sont abordés. Les études qui portent sur les mineurs d'uranium des États-Unis, de l'Ontario et de la Tchécoslovaquie sont réexaminées, afin de constituer la meilleure base d'information utilisable pour évaluer les risques.

De façon générale, aucune des analyses n'est incompatible avec une relation exposition-effet linéaire. De plus, à la suite des analyses de tous les groupes de mineurs, on observe que les intervalles les plus probables des coefficients de risques absolu et relatif sont respectivement de 5 à 15 cas par million par année-personne par unité alpha-mois et de 0,5 à 1,5 pour 100 par unité alpha-mois.

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1.0 INTRODUCTION

Mining of radioactive ores in Central Europe began as early as the 15th century. By 1556 Agricola described an unusual fatal chest disease that occurred in miners of this region (Myers et al., 1981; Stewart and Simpson, 1964). However, the actual nature of the disease was not recognized until much later. Indeed, it was only in the early 20th century that the illness was recognized as lung cancer. Although the miners' disease had been studied by various investigators, there was no consensus as to the causative agent in the Central European mines. Among the agents suspected were mine dust, arsenic and various metals in the ore. Pirchan and Sikl (1932) suggest that radioactivity in the Joachimsthal and Schneeberg mines was the likely causative agent responsible for the increased risk of lung cancer.

During the 1930s and 1940s, radioactive ores were mined in several countries, including Canada, as a source of radium for medical purposes and luminescent dials. Other radioactive ores were mined as a source of nonradioactive materials such as vanadium. However, extensive uranium mining did not begin until the later 1940s. From the early 1950s onwards, uranium mining was carried out on a large scale in several countries including the United States, Canada and Czechoslovakia. Subsequently, a number of detailed epidemiological studies were initiated and performed on the various groups of uranium miners in Canada, the United States and Czechoslovakia. Studies were also carried out on various groups of non-uranium miners who were exposed to elevated levels of radon daughters. These studies include the Newfoundland fluorspar miners and the Swedish iron miners.

All these studies found an increasing risk with increasing exposure to radon daughters. However, the increased risk per unit exposure estimated from each of these studies differ

substantially. There are a number of possible reasons for these differences: simple statistical variability (as for example that due to small numbers of cases); the effect of co-variables such as smoking or exposure to other potential causative agents; age at start of exposure or at time of death; differences in other factors between the study group and the comparison group; and various characteristics of the exposure variable itself such as the rate of exposure and total cumulative exposure. A recent report by the BEIR IV committee (1988) of the U.S. National Academy of Sciences discusses several factors which can contribute to uncertainty in the risk projections and which may contribute to differences among the various studies.

In the present study, we focus on one particular issue, namely the role of uncertainty in the exposure (WLM) variable. This is an important consideration since the epidemiological analyses form the principle basis from which radon daughter lung cancer risk coefficients are estimated. This is of practical importance not only for men working in mines, but also for evaluating the potential effects of radon daughter exposure at home.

In view of such considerations, the Atomic Energy Control Board (AECB) asked SENES to investigate:

- 1) the level of uncertainty attached to exposure estimates derived from various epidemiological studies, and
- 2) the potential effect of uncertainty in the exposure variable on risk estimation.

This report outlines the results of the SENES study.

The principal SENES investigator was Dr. Douglas B. Chambers who was assisted by Dr. Leo M. Lowe. The contribution of Dr. Park Reilly of the University of Waterloo is gratefully acknowledged,

as Dr. Reilly was instrumental in the development of the error-in-variables model (EVM) described later in this report.

Various subjects discussed in this report are described in the following chapters.

CHAPTER 2.0 - EPIDEMIOLOGICAL STUDIES CONSIDERED

In this chapter, we briefly review the nature of the epidemiological studies which have been performed on seven study groups; namely, U.S. (Colorado) miners, Ontario miners, Czechoslovakian miners, Beaverlodge miners, Port Radium miners, Newfoundland fluorspar miners and Swedish iron ore miners.

Further information on each of these miner study groups is provided in Appendices A through G, respectively.

CHAPTER 3.0 - SOURCES OF UNCERTAINTY IN EXPOSURE ESTIMATION

In this chapter, we review the various possible sources of uncertainty in exposure estimation. These include not only factors which affect estimation of radon daughter concentrations themselves, but also factors which affect our understanding of individual miner's work histories. Several examples illustrating the effect of different factors are provided.

CHAPTER 4.0 - THE EFFECT OF UNCERTAINTY ON RISK ESTIMATES

In Chapter 4, we discuss the effect of uncertainty on the estimated risk and present two approaches for incorporating uncertainty directly in the risk estimation process.

Detailed descriptions with mathematical formulations of the two methods developed in this study are provided in Appendices H and I.

CHAPTER 5.0 - DISCUSSION

Chapter 5 presents an overview of the findings of this study with regard to the major sources of uncertainty in exposure estimation and their effects on the estimation of risk coefficients. In addition, we have attempted to evaluate a likely range of risk coefficients for both attributable and relative risk models.

APPENDICES

Appendices A through G provide additional information and bibliographic citations for the epidemiological studies considered which complement the discussions in the main text.

Appendices H and I set out the mathematical formulations for the two approaches used in this study to examine the effect of exposure uncertainty on risk.

2.0 EPIDEMIOLOGICAL STUDIES CONSIDERED

2.1 Introduction

In this Chapter, we review the basic epidemiological data from which estimates of risk associated with exposure to radon daughters are derived. At the outset however, we wish to briefly describe some basic epidemiological considerations which affect the interpretation of the epidemiological studies themselves and the estimation of risk therefrom.

Measures of Risk

There are a number of ways in which risk can be defined and measured. In this study however, we simply mean by risk the chance or probability that a miner might develop lung cancer following exposure to radon daughters. (Note that we do not attempt to analyze the factors involved in extrapolating risks derived from miner studies to the general public.)

We refer to two measures of risk in this present report. The first is "attributable" risk which is simply the difference in risk of lung cancer between exposed and unexposed groups. (In radiation protection literature, "attributable" risk is often called "absolute" risk although absolute risk normally refers to the incidence of a disease, here lung cancer.) The second measure of risk is termed "relative" risk. The relative risk is simply the ratio of the rate of occurrence of a particular end-point (here, lung cancer) in the exposed group to that in a comparable non-exposed group (i.e. the ratio of the observed cases/expected cases).

For expressing the results of any particular study, the choice between absolute and relative risk is merely one of

convenience. However, there are considerable differences between these two indices when prediction of a lifetime risk is required. Such considerations are beyond the scope of this study. The reader interested in such matters is referred to reports such as that of the BEIR IV Committee (1988).

Excess Risk

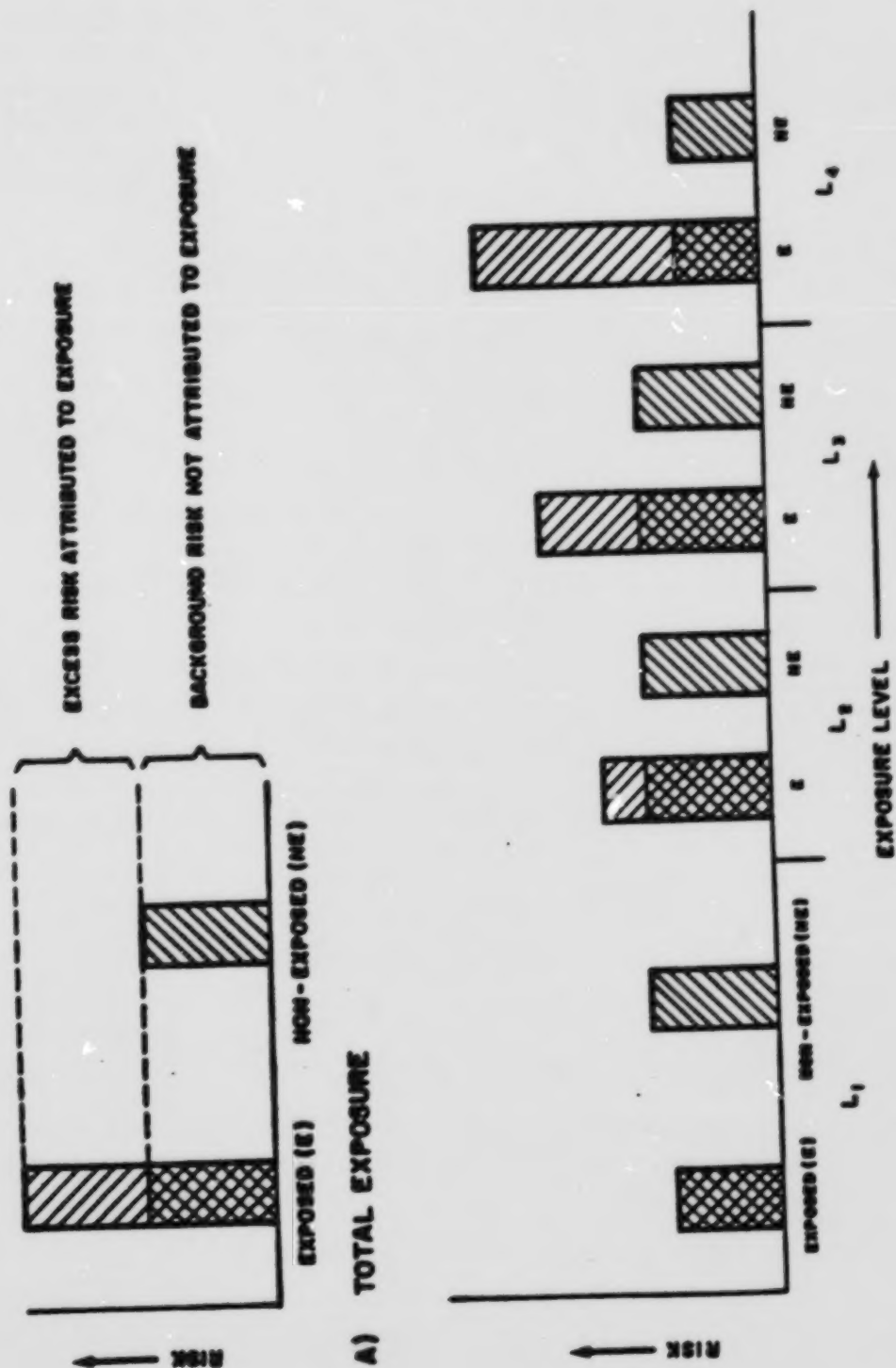
In Figure 2.1, we attempt to illustrate the concept of risk in an exposed group and in a directly comparable non-exposed group.

Part A of Figure 2.1 illustrates the concept for a group of persons who are exposed to a certain factor which carries some risk. We can see from this figure that the exposed group is subjected to the risk from natural background causes, as well as an excess risk which can be attributed to the exposure under consideration.

In developing such data, it is important to emphasize that the two groups (i.e. those exposed and those non-exposed) must be comparable with regard to variables such as age, smoking habits and other factors which have potential to affect the risk estimation.

While composite data such as that illustrated in Figure 2.1(A) are informative and indicate a positive association between exposure and risk, they are not very helpful with regard to an understanding of exposure and response. In order to extract an exposure-response relation from a study, it is necessary to stratify the excess risk to the exposed group by level of exposure. This concept is illustrated on Figure 2.1(B).

FIGURE 2.1
RISKS IN EXPOSED AND NON-EXPOSED GROUPS



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We emphasize that it is necessary to do the utmost to ensure that the non-exposed group is as comparable as possible to the exposed group. Typically, data such as that illustrated in Figure 2.1(B), can be used in some form of regression analysis to extract relationships between increasing exposure and increasing risk. This is exactly what has been done with the uranium miner investigations. In many instances, simple linear exposure-effect relationships have been examined, although some investigators have considered more complex exposure response and time-exposure-response models. The examination of such aspects was beyond the scope of the present study, and readers interested in such considerations are referred to recent reports of the BEIR IV Committee (1988), NCRP Report No. 78 (1984), the Ontario Miner Study (Muller et al., 1987), and the study of Thomas and McNeil (1982).

The present study focuses on uncertainty in WLM exposure and its effect on linear exposure-effect relationships; however, it must be made clear that the statistical methods outlined in Chapter 4 and Appendices H and I can be applied to subsets of the overall data or to the analyses of more sophisticated models, such as the time-since-exposure model used by Muller et al. (1987) to examine the Ontario miners.

WLM Exposure

As previously stated, the focus of the present study is uncertainty about the exposure variable and its effect on risk estimation. Davies (1985) has noted that "a general problem is the lack of comparability between different studies not only in the data used but in the methods of analyses. This is particularly true of exposure data. To quote Petersen and Sever (1982, p. 23): "sources vary widely in:

- 1) the number of measurements made,
- 2) the years in which measurements were made,
- 3) the extent of estimation used to assign exposures to individual miners,
- 4) the magnitude of actual exposures, and
- 5) the number of person-years of observation for risk.

In addition, widely differing methods were used to estimate exposures to radiation and to measure response in relation to exposure. As a result of this diversity of information and inadequacy of the analytic methods, interpretations must be viewed with caution."

Davies (1985, Para. 96) notes: "In the past some mines have had highly mobile labour forces, and, although records may provide a full history of a man's employment and exposure of the mine under study, there may be uncertainties about his possible exposure at other mines."

Davies (1985), and earlier Petersen and Sever (1982), have thus clearly identified some of the major considerations which influence the uncertainty in WL and WLM exposure estimation. Both Davies, and Petersen and Sever also discuss differences among the studies and the ways the exposure data are actually used.

Some of the factors that might affect radon daughter concentrations and exposure estimation include ore grade, mining method, and ventilation practice. The role of these and other factors are discussed in Chapter 3.

Epidemiological Data

The basic nature of epidemiological data on which current risks

estimates are based is outlined below. Some key data from the various studies are summarized in Table 2.1. Risk coefficients estimated for the various studies are also provided. Lung cancers appearing less than 5-10 years after the first exposure are usually excluded in the calculations to ensure better comparability of the data from short and long term follow-up, and to ensure that the risk coefficients are not too low because of inclusion of years of follow-up during which no effects of radon daughter exposure are anticipated. Overall, the data in Table 2.1 represent average risk coefficients observed between 5 and 10 years after first exposure and the end of follow-up

As implied previously, a major problem in all these studies is the reliability of exposure estimates. In general, exposure rates were highest during the earliest years of mining and decreased, primarily through the introduction of improved ventilation practices, in later years. However, monitoring of radon daughter concentrations was either infrequent or absent during the earliest years of mining. Therefore, exposure histories of the early miners with the highest exposures and longest follow-up have necessarily been reconstructed from minimal data.

2.2 U.S. (Colorado) Miner Study

The exposure of underground U.S. miners to radon has been the subject of numerous published papers. The primary source of information for exposure data (and indeed all data concerning the U.S. public health service cohort of men) is the 1971 Joint Monograph by the National Institute for Occupational Safety and Health (Lundin et al., 1971). As described in the Joint Monograph, starting about 1950 the U.S. Public Health Service began to collect data on uranium miners in Colorado, Arizona, New Mexico and Utah. These data included radiation exposure, smoking histories, and mortality follow-up.

Numerous analyses of these data with different periods of follow-up have been published, including those of Lundin et al. (1971), Archer et al. (1978), Waxweiler et al. (1981), Whittemore and McMillan (1983), Hornung and Meinhardt (1987) and BEIR IV (1988).

According to Lundin et al. (1971), the first radon gas measurements in U.S. mines were made in 1949 and the first radon daughter measurements were made in 1951. In 1952 an effort was made to survey every operating mine and during that year radon daughter samples were collected in 157 mines. Radon gas samples were also obtained in 79 mines. In 1953-1954 the number of surveys was limited, but in 1955 many of the larger uranium mining companies initiated their own air sampling programs. By 1956, most of the survey work was being done by mining companies.

Lundin et al. (1971) emphasize the large numbers of measurements made in the mines: *"From the entire 1951-1968 nearly 43,000 measurements of radon daughter concentrations were available to characterize the approximately 2500 uranium mines from which ore was shipped"* (p. 31). They do not emphasize however that this represents typically less than one measurement per mine year averaged over eighteen years of study.

Moreover, the distribution of exposure measurements was far from uniform. In some mines no measurements may have been made while in other mines fairly large numbers of measurements might have been made. Lundin et al. (1971) tabulate (Table 19, page 34) the number of mines in which five or more radon daughter measurements were made in any one year. The sum of the number of mines sampled more than five times in a year amounts to only 116 mine years for the years 1951 - 1954 when more than half of the total exposure was received. For the period 1955-1968 the total number of mine-years for which there are more than five measurements was 1,313.

Table 2.1

ESTIMATES OF RISK OF EXCESS LUNG CANCER IN VARIOUS GROUPS OF MINERS

Group (approximate no. of miners)	Average estimated exposure (WLM)	% Increase in normal incidence per WLM	Excess cancers per 10 ⁶ person years per WLM	Reference
U.S. Uranium (3,366) all white	828 ¹	- 0.31 1.47 ²	6 ¹ -	BEIR III (U.S. NAS, 1980) Whittemore and McMillan (1983) (smoking correction) Hornung and Meinhardt (1987)
(1924) U only	818 ⁴	0.31 ³	5.7 ³	SENES (1988)
Ontario Uranium ⁵ (15,984)	53	1.3 0.5	5.2 2.1	Muller <u>et al.</u> (1984) standard WLM special WLM
Czech Uranium ⁶ (2,433)	310	1.5	20	Sevc <u>et al.</u> , Group A miners (1988)
Eldorado Beaverlodge (8,487)	20.2 ⁷	3.2	20.8	Howe <u>et al.</u> (1986)
Eldorado Port Radium (2,103)	183.3 ⁸	0.27	3.1	Howe <u>et al.</u> (1987)
Malmberget (Sweden) (1,415)	81.4	3.6	19	Radford and St. Clair Renard (1984)
NFLD. Fluorspar (1772)	360	0.89	6.3	Morrison <u>et al.</u> (1988)

Note :

1. Calculated for groups with low exposure (<360 WLM).
2. For cumulative exposure of 30 WLM.
3. For uranium miners with no other hardrock experience.
4. Exposures include WLM only from underground uranium.
5. No prior gold mining.
6. Study population of Czech miners starting 1948-1952 from Sevc and Jerabek (1971).
7. 52% of person-years at risk are in category <5 WLM.
8. 42% of person-years at risk are in category <5 WLM.



With regard to exposure measurements, an earlier study by the advisory council of the U.S. National Academy of Sciences (U.S. NAS, 1968) observed that "Exposure values assigned to the period before 1956 are highly unreliable, being based almost entirely on estimates rather than measurements of concentrations." (p. 7)

The exposure estimates used in the monograph of Lundin et al. (1971) were based on radon daughter concentrations derived in one of three ways:

- 1) "measured" - measured values were derived directly from one or more measurements of radon daughter concentrations in any given mine in a given calendar year. Before 1955, such "measured data" included few work areas in the mine.
- 2) "extrapolated" - extrapolated concentrations were obtained by extrapolating between measurements made in other years in the same mine but not more than 2 years before or after the year for which extrapolation was made. In some cases, regional extrapolations were also made for mines having no direct measurements by assigning a concentration value equal to the average for the other mines in the vicinity.
- 3) "guestimates" were provided by Mr. Holaday for mines in which radon daughter concentrations could not be obtained by any of the extrapolation techniques discussed in Lundin et al. (1971). The guestimates were based on general knowledge of airborne concentrations that had occurred in similar mines during the same time period and of long term trends.

Reporting on interviews with Mr. Holaday, Schiager and Hersloff (1984) note that Mr. Holaday emphasized that, while large uncertainties exist in the air concentration estimates, they were the best estimates that could be made, and there was no conscious

bias injected into the estimates of early exposure conditions. This is in contrast to statements in the Joint Monograph which indicate that, where uncertainties existed exposures were deliberately overestimated (Lundin et al., 1971, p. 2, 31, 44, 112). If, on average, exposures were overestimated, then on average the risk per unit exposure would be underestimated.

As noted previously, mining companies began making most of the exposure measurements after 1956. Lundin et al. (1971) felt there was a possibility of a bias during this period (to underestimation of exposure) and therefore these authors tried to avoid this potential bias "...efforts were made to exclude company measurements from data after 1960 from use in the epidemiological study of uranium miners" (p. 31). However, since the bulk of the exposures upon which risk estimates are based occurred prior to 1960, this selection had very little impact on the results.

Overall, it seems fair to say that exposures estimates for U.S. Colorado Plateau miners for the period before 1950 are most unreliable as there are no data and all the estimates are based on extrapolation and "guestimates". Exposures estimated for the period 1950-1956 are somewhat more reliable although still highly uncertain. While the sampling frequencies increased during this period, some of the measurements may still be in considerable error. After 1956, the companies started measurements on a systematic basis and, at least in the large mines, measurements became more reliable. However, there is still likely to be considerable uncertainty in exposure assessment until what one might refer to as the "modern period", i.e. from 1967 to the present.

Cumulative WLM Estimates

The exposures received only in uranium mines by white underground uranium miners forms the primary basis for the epidemiological risk estimates.

According to Lundin et al. (1971, Table 32, p. 60), more than 50% of the collective exposure of some 2.8 million person-WLM was received prior to 1955. For the cumulative exposure received through 30 September 1960 by 3325 men, the monograph states that more than 25% of the calculated person-WLM for 1325 men was based on actual measurements (Lundin et al., p. 44-46). Although the converse is not explicitly stated, it seems reasonable that for 2000 men in this cohort less than 25% of the cumulative exposure was based fully on measured data. This emphasizes the uncertainties in the early exposure data; however, it does not necessarily imply any bias in exposure estimates (and hence in the risk estimates).

The durations and times of exposure of individual miners were determined in some cases from employment records but in most instances from interviews with the miners themselves. Annual exposures for full-time miners were assigned on the basis of radon daughter concentrations averaged throughout the mines where each miner worked. For calculated annual exposures, "...it was assumed, unless we had information to the contrary, that a man worked in the mine at which he was found for six months before and six months after the census or questionnaire date (6 month rule). When a man was known to work in two different mines at less than a one year interval, the period of employment during the interval was equally divided between the two mines" (ibid p.56).

Full-time mining was assumed to consist of 12 full months

underground with no corrections for vacations or sickness. This assumption has been pointed out by Dr. Archer as being one the important reasons for believing that exposures were overestimated. However, Archer has also acknowledged there are also no corrections made for overtime work or "moonlighting" by any of the miners (Schiager and Hersloff, 1984). People familiar with uranium mining industry in the 1940's and 1950's will recall that many miners worked exceptionally long hours. A standard work week until 1960 was at least 48 hours. Many miners working entirely under production contracts spent 50-60 hours underground each week. It was not unusual for a miner to work a regular full-time shift for an established company and spend his days off developing a mining claim of his own. Since estimates of cumulative exposures (i.e. WLM) were based on months rather than hours worked, the method tended to underestimate exposures during periods of long work hours. It is likely therefore that any potential bias in exposure estimates resulting from not making allowances for vacation and sickness were more than compensated for by not making allowances for underground time exceeding the normal (48 hour) work week.

As noted in the 1968 report of the National Academy of Sciences (NAS, 1968) the problem of determining individual uranium miner's radiation exposure is complicated by the fact that official mine records do not necessarily show his actual job assignment. Only the miner himself, and to the lesser extent his immediate supervisor know the areas in which he has worked. The report also raises the possible problem of exposure from previous mining.

The 1968 NAS report notes that "there is some uncertainty in the average working values even in mines in which numbers of measurements have been made." The report notes that the measurements which consist of spot sampling at a particular time

and location will therefore reflect the conditions that existed at that time and location. (This is important since exposure in WLM is the product of time in working months (nominally 170 hours) and radon daughter concentration in WL.) The report recognizes that conditions can vary with the nature of mine operations such as blasting, ventilation and the amount of ore uncovered.

According to a review of the U.S. PHS epidemiological study (Joint Committee on Atomic Energy, 1967, p. 1266), the following basic information on individual uranium miners was examined:

- 1) mines worked
- 2) dates of employment in mines;
- 3) fractional time in mines; and
- 4) working levels measured or estimated for each mine as a functional calendar year.

From these data, values of cumulative WLM were calculated for each individual miner. Cumulative WLM values were calculated for both underground uranium mining alone and for uranium mining plus other hard rock (OHR) mining.

OHR

Exposures from OHR mining were calculated according to a prescription recommended by Lundin (1969), the procedure employed in the U.S. PHS investigations. As set forth by Lundin, a miner was assumed to have completed all his OHR by the year preceding his start of underground uranium mining. Exposures were based on assumed radon daughter concentrations in OHR mines of 1.0 WL prior to 1935, 0.5 WL from 1935-39, and 0.3 WL from 1940 on.

Table 2.2 is a summary of the average exposures of miners from

uranium mining only and from OHR mining. Except for the first two exposure categories, OHR is only a relatively small contributor to the total WLM and it might therefore appear that OHR exposure is not an important factor. However, consider Table 2.3 which lists the 10 lung cancer cases (with follow-up through 31 December, 1982) in the 0-120 WLM category based on uranium only exposure. When OHR exposure is added, five of the ten miners are shifted from the 0-120 WLM category into the next higher exposure category. Thus, particularly in the low exposure categories, which are of most interest to modern day miners, there is a potential bias introduced by the neglect of OHR exposure.

Studies done by Muller et al. (e.g. 1984) on Ontario miners also show a marked effect of OHR mining exposure on the risk estimation. Such analyses suggest that it would be preferable to carry out exposure-response evaluations on populations of miners with experience in only uranium mines or, alternatively, in only a single type of mining environment. There is clearly some factor, whether radon or something else, that influences the risk estimation process.

It is perhaps relevant to note that radon does occur in non-uranium mines in the U.S. For example, Holaday (1955) reports results of several early measurements of radon in non-uranium mines in Colorado and New York. Radon levels surveyed in 35 metal and clay mines in Colorado ranged from 10 to 2100 pCi/L. In the New York mines, radon concentrations ranged from 2 to 110 pCi/L. As noted by Holaday, these surveys suggest that radon is a normal constituent of mine atmospheres. More recent data reported by NIOSH (1987) also demonstrate this fact.

Overall, our opinion is that while the estimates of exposure to underground U.S. uranium miners are highly uncertain, there is no

Table 2.2

WLM EXPOSURES OF U.S. MINERS*

Underground

Uranium

Mining

Exposure

Category (WLM)

Lung Cancer Cases

Uranium

Other Hard

Mining

Rock Mining

Total

All Miners

Uranium

Other Hard

Mining

Rock Mining

Total

0-119.9	51	65	116	52	16	68
120-359.9	251	39	289	233	16	249
360-839.9	593	40	634	573	21	594
840-1799.9	1255	33	1288	1230	22	1252
1800-3719.9	2560	22	2582	2515	19	2533
3720+	6005	12	6017	5794	21	5815

Source: SENES, 1988.

Note:

- * WLM values given in Table are average values calculated from NIOSH records for miners in specified exposure category, i.e. the average exposure to miners in the 0-119.9 WLM category from uranium mining only is calculated to be about 51 WLM; etc.

Table 2.3

EFFECT OF OHR FOR LUNG CANCERS CASES IN U.S. MINERS WITH
LESS THAN 120 WLM URANIUM MINING EXPOSURE

SENES			
ID	Uranium mining	OHR* mining	Total
<u>Number</u>	<u>exposure (WLM)</u>	<u>exposure (WLM)</u>	<u>exposure (WLM)</u>
1911	8	0	8
1011	13	136	149
1092	28	0	28
3321	33	0	33
3297	42	187	229
3588	44	62	106
2023	68	29	97
1563	73	68	141
534	83	122	205
560	<u>119</u>	<u>44</u>	<u>163</u>
Average	51	65	116

Note:

* OHR mining = other hard rock mining

Source: SENES, 1988.

clear evidence of significant bias.

As of 31 December 1982, the U.S. PHS study group consisted of 3356 white underground uranium miners, of whom some 2024 men were still alive, and in which some 259 lung cancers had been observed. For the study group as a whole, the average cumulative exposure to radon daughters was approximately 830 WLM. In the men with lung cancers, the average exposure was approximately 1882 WLM.

2.3 Ontario Miners

Muller and his co-workers have carried out studies on some 50,000 men who worked in one or more mines in Ontario (e.g. Muller et al., 1983, 1984, 1987).

The Ontario miner population was subdivided into gold miners, nickel copper miners, iron ore miners, uranium miners, other ore miners and a mixture of miners. Men who had exposure in Eldorado's Port Hope plants or in Eldorado mines in Saskatchewan or the Northwest Territories, as well as men with exposure to asbestos, were excluded from the Ontario study. In the remainder, there were about 15000 miners with exposure in Ontario uranium mines.

In Ontario, uranium mining started in 1955. Men entered the study at the time of their first medical examination between 1 January 1955 and 1 January 1978, when they reported having worked for half a month or more in dust exposure in an Ontario uranium mine. Miners left the study in 31 December 1981 or at death which ever occurred earlier. As noted previously, men with known exposure to asbestos fibres and men with work histories in uranium mines outside Ontario were treated separately in the study.

The Ontario studies have demonstrated the importance of OHR mining experience in that uranium miners with previous gold mining experience are subject to an excess risk of lung cancer even at zero WLM exposure.

Over the period 1955 to 1981, some 131,000 measurements of radon daughters were made using the Kusnetz method. These data were obtained over a period representing some 141 mine-years of operation, which corresponds to about 929 measurements per mine-year of operation. Up to 1977 there were approximately 55,000 measurements accumulated over some 126 mine years of operation, which corresponds to approximately 430 measurements per mine-year of operation over this period. In the earlier period, from 1955-1977, an average of approximately 1.7 measurements were made per man-year worked. On average, for every 9 WLM accumulated by the study cohort, one WL measurement was made.

About 23% of the assigned WLM exposure of the cohort is based on extrapolated values of radon daughters, particularly during the early years of mining. The mean period of extrapolation weighted by WLM exposure is approximately 1.1 years. These and other key observations are summarized in Table 2.4. Table 2.5 shows a distribution of population WLM exposure based on extrapolated WL values.

The Ontario investigators also recognized that the estimation of radon daughter levels involved some uncertainty, especially for the early years of mining for which relatively few reliable measurements are available. Recognizing this uncertainty, Muller and his co-workers developed two estimates of exposure, "standard" and "special" WL, to try and bracket the uncertainty. The WL estimation procedure was developed by mining engineers who were familiar with the Ontario uranium mines over the early years of operation (Muller et al., 1983). Muller and his co-workers

Table 2.4

**KEY FACTORS IN THE ESTIMATION OF
RADON DAUGHTER EXPOSURES IN ONTARIO MINES**

<u>Year</u>		
1955		2 uranium mines, sporadic measurements
1958		15 uranium mines, systematic measurements . 80% time heading stope raises . 20% travelways
1955-1981	-	131,000 radon daughter measurements over 141 mine years of operation, average 929 per mine year (fewer in early years)
	-	mean extrapolation period (pre-1958) 1.1 years (23% of total population WLM)
	-	standard and "special" WL by mine and calendar year
	-	standard WL considered "more representative"

Source: Muller et al. (1987).

Table 2.5

POPULATION WLM EXPOSURE OF ONTARIO MINERS BASED ON
EXTRAPOLATED WL VALUES

<u>Calendar Year</u>	<u>Extrapolated Standard WLM</u>	<u>Total Standard WLM</u>	<u>Percent WLM Based on Extrapolation</u>
1954	843	843	100
1955	4276	4276	100
1956	20806	20806	100
1957	52263	52263	100
1958	9736	87048	11
1959	10617	81733	13
1960	12902	55275	23
<u>1961-77</u>	<u>0</u>	<u>185079</u>	<u>0</u>
TOTAL	111443	487323	23

Source: Muller et al., 1987.

suggest that the standard WL estimate is perhaps more representative of a miner's exposure while the special WL estimate may be somewhat on the high side.

Up to the end of 1967 and in one mine up to the end of 1 April 1968, WLM exposure values for each miner were estimated as $WLM = WL \times WHF \times \text{months}$, where WHF is the work history factor, WL is the weighted average of WL measurements in stopes, raises and travelways, and months are the months worked underground.

The Ontario investigators set the work history factor (WHF) equal to unity if normal working hours were maintained. The WHF was increased or decreased as appropriate if overtime hours were worked or work stoppages occurred in a particular calendar year.

After 1967, the individual exposure estimates were based on the time card which was filled out daily by the miner and on WL measurements made in the work locations reported by the miner on his time card.

Smoking information on the Ontario uranium miners is very incomplete. The most recent study of Muller *et al.* (1987) report on the results of a 3% sample of men born prior to 1939. Smoking information was sought on 226 uranium miners with no former gold mining experience. Smoking information was also sought on 80 lung cancer cases, deaths that occurred between 1955 and 1981 in the cohort of uranium miners with no former gold mining experience. Of the 80 lung cancer deaths among men with no former gold mining experience, smoking information was obtained on 73 men (90% recovery). Of these, 72 were smokers or former smokers (Muller, 1988).

Finally, it is worth noting that the group of underground uranium miners examined by Muller *et al.* (1987) included some 14,877 men

with 279,417 years of observation to the end of 1981. To the end of 1981, 80 deaths from lung cancer had been reported in this group of underground uranium miners with no gold mining experience prior to becoming uranium miners. Ninety-two deaths from lung cancer occurred in men who had worked as gold miners before becoming underground uranium miners. Finally, it is worth noting that a typical uranium miner had, as of 1984, 1.5 years of mining experience and median age of 39 years. Overall, there was an average of 15.1 person-years at risk per man. Muller et al. (1984) also report mean exposures in the range of 40-90 WLM for this group.

2.4 Czechoslovakian Miner Study

Czechoslovakian investigators have studied several groups of underground uranium miners. The most studied group is referred to as Group A, which consists of Czech miners who were exposed in the period between 1948-1952. This group included 2,433 men (see Sevc et al., 1971). By 1979, Kunz et al. note that the total of Group A miners had an average of about 26 years of experience which implied approximately 63,000 person-years at risk for the group. These authors also note that the risk factors derived from Czech data had not yet been corrected for smoking habits. According to BEIR III (1980, p. 317) the mean exposure of this group of Czech miners was approximately 300 WLM. Czech papers do not usually indicate the numbers of miners involved and therefore it is sometimes necessary to back-calculate from reported data as to the number of miners in the various groups.

More recently (e.g. Sevc et al., 1988; and Kunz et al., 1988), the Czechs report investigations of other study groups which include study Group S with subgroups A and B covering the underground uranium miners starting exposure in 1948 and in 1957, respectively and which represent the main Czech epidemiological

investigations. In addition, the Czechs also report investigations of study Group N which comprises uranium miners starting exposure at levels lower than those in study Group S. Finally, the Czechs report results for a small study K which comprises miners in east Slovakian iron mines and study L on miners from Czech shale-clay miners.

In the older study S, the cumulative exposure of miners was calculated on the basis of registered shifts and more than 120,000 radon measurements. Typically, there was a minimum of 100 measurements per mine per year. Prior to 1960, radon daughter levels were estimated from radon gas levels using equilibrium factors calculated according to mining data and ventilation volumes.

In December 1988 a group of investigators including one of the authors (Chambers) met with Drs. Kunz, Sevc and Thomas in Prague. Much of the following information was derived from that meeting. The Czechs note that in 1968 and again in 1973, there were ventilation accidents in underground uranium mines. In both situations, mechanical ventilation was stopped and there was only natural ventilation for a period of time. During the upsets, the Czechs measured radon/radon daughter levels and assessed the equilibrium conditions which might have existed in the early days of mining prior to mechanical ventilation. These data provide useful insight as to past radon daughter levels. Based on these two accidents, the Czechs assumed (typically) an overall equilibrium factor of approximately 86% for the period 1948 to 1952, noting however that in some of the newer mines the situation was better. From 1953-1959, the Czechs assumed a nominal equilibrium factor of approximately 55%. For the period 1960-1966, the Czechs assumed a radon equilibrium factor of 36% noting that some of the older mines had higher equilibrium fractions and in some of the newer mines the equilibrium fractions were lower.

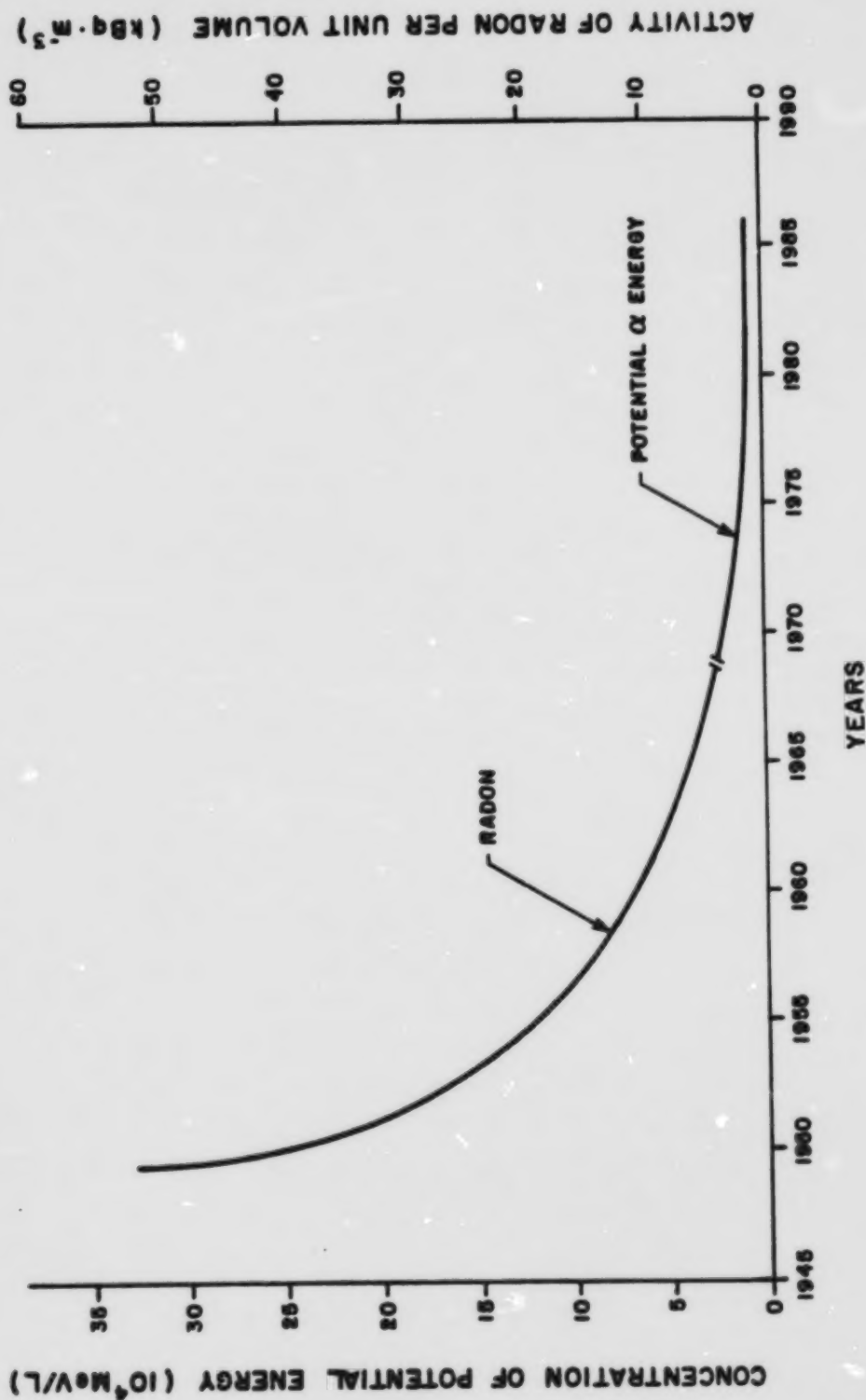
From recent discussions with Czech investigators, it appears that from start up of the mines after the second world war until approximately 1952 natural ventilation was widely used in the mines. Mechanical ventilation started seriously about 1953 and, from 1955 onwards all the mines were mechanically ventilated. After 1955, secondary (auxiliary) ventilation was also provided. The Czechs noted that from 1946 onwards, the individual mining companies had good in-house services for making radon measurements. From about 1960 onwards, the Czechs measured radon daughter levels in selected workplaces. Full measurements of radon/radon daughters by mining companies was started only after 1966.

During the period 1948-1952, there was natural ventilation in the western Bohemia uranium mines and 40% of the measurements indicated levels in excess of 1000 pCi/L. The early high radon levels and the improvements that took place are illustrated on Figure 2.2. The break in the curve shown on Figure 2.2 reflects the change from routine radon measurements to routine radon daughter measurements as a primary basis for estimation.

The Czechs also discussed various statistical evaluations they have done concerning the reliability of the data. Periodically, the Czechs re-evaluate the basis for the exposure estimation and most recently have calculated the coefficient of variation for the conversion of radon to WL as 27%.

Sevc indicated that they have estimated a coefficient of variation for an individual miner cumulative WLM of about 28%. He explained that this (relatively) high accuracy is due to the large number of radon measurements which were made. Sevc noted that coefficient of variation for the cumulative exposure of the Czech miners as a group is in the order of 1.3 to 1.8%.

FIGURE 2.2
THE DEVELOPMENT OF THE AVERAGE VOLUME ACTIVITIES OF RADON (1949-1968)
AND THE AVERAGE POTENTIAL (ALPHA) ENERGY CONCENTRATION (1969-1981)



SOURCE: PERSONAL COMMUNICATION WITH KUNZ, 1988

The Czechs also indicated in general terms that the measurements of radon were divided in accordance with four working areas:

- 1) mine work places in close proximity to the ore where the levels were the second highest in the mine;
- 2) hallways and corridors where there was no ore;
- 3) chimneys (raises) where the levels were the highest; and finally
- 4) transport ways.

Where no data on a workplace existed, the Czechs took the average value for the mine in a given year. Typically, 20% of the total numbers of measurements were made in transport ways and 80% of the measurements were made in the workplaces. Until 1968, there were 6 working days per week, and the shifts were 8 hours per day. The Czechs noted that for study Group S it was assumed the men worked six days per week.

Based on recent (preliminary) surveys, the Czechs estimate exposure to radon in normal areas of Czechoslovakia to be about 0.34 WLM/y, whereas some residents of the Joachimsthal area could be exposed at 3 to 4 WLM/y. Preliminary evaluations by the Czechs suggest that correction for at-home exposure, which shifts men to higher exposure categories, did not affect the risk estimates very much. The role of natural radiation is subject to ongoing investigation.

Miner's individual exposures were calculated on the basis of job descriptions, records kept by the men themselves of where they worked and personnel cards for all miners which were started in 1948 for pay control. The Czechs noted that there was a controller watching the miners and it was the job of the mine technician to rate the workers pay. Technicians also had to correlate the meters of advance with production. Therefore, the

Czechs feel fairly comfortable with the estimates of time spent in the workplace.

Overall, the quality of the Czech exposure data must be rated very highly.

2.5 Beaverlodge Miner Study

History

At Beaverlodge, the Ace shaft was started as a prospect shaft in 1949. By 1951, sufficient ore had been identified to permit proceeding with production operations. Orebodies to the west of the Ace shaft had also been identified. The Fay shaft was started in 1951 as a production shaft serving the western ore bodies and, by means of underground haulage way, it also served the Ace ore body. By 1953, work had also started on the Verna shaft where production work started in 1956. As the mine developed all three shafts were connected underground and two winzes (underground shafts which do not come to surface) were developed.

By the late 1970s, the mine complex was more than one mile (1.6 km) deep and extended over 3.5 miles (5.6 km) horizontally. In the early 1950's just as the mining operations at Beaverlodge were coming into production, there was an increasing recognition of the potential health hazards in uranium mines associated with radon and radon daughters.

Epidemiology

Howe et al. (1986) report on a study of Beaverlodge miners which is a part of a larger study of some 18,000 Eldorado employees. The Eldorado epidemiology project has been followed in a series

of papers published by Eldorado (1987). Due to the size of the study population, Howe et al. were not able to interview the Eldorado employees. The exposure reconstruction had to rely on work history files from Eldorado. It was therefore possible that the work histories of the study cohort could be deficient with regard to non-Eldorado employment. This observation is important because miners could have worked in other mines for which no radiation exposure data are available.

According to Howe et al. (1986), all exposures prior to 1 November 1966 were recorded as single lifetime totals rather than separate annual totals making them less useful for epidemiological purposes. (The authors note that the actual year-to-year variability in mine conditions were available for the epidemiological study). In calculating annual exposure, Howe et al. note: "We used the radon measurements by establishing a radon daughter equilibrium factor for each year from parallel radon and radon daughter measurements and using this factor to convert radon concentrations to equivalent radon daughter concentrations" (ibid p. 350). These authors also indicate that the (annual) median value was used to describe (annual) average WLS.

The Eldorado epidemiology study has 19,370 male work records for only 18,424 persons, meaning that up to 946 individuals worked at more than one Eldorado site (Nair et al., 1984). It is known that many of these men worked at Port Radium, Eldorado's first mine and therefore, some of the miners in the Beaverlodge study could have received exposure while at Port Radium.

The mortality study of Ontario miners (Muller et al., 1983) has also identified 1430 former Eldorado employees, who worked in Ontario mines, 726 of whom worked in Ontario uranium mines. No known Eldorado exposure estimates for these men have been included in this study.

Because of the remote location, the cost of recruiting at Beaverlodge was high; consequently, Eldorado's policy was to recruit experienced miners wherever possible. In some instances when experienced miners were not available in Canada, Eldorado recruited miners from Europe. It is less likely that the European miners had uranium experience but, whatever their exposure, there is no estimate of their non-Eldorado experience.

Miners from other western Canada uranium mines may be a more significant group in terms of non-Eldorado exposure. During the early years of Beaverlodge, some 28 other uranium mines were operating at the same time as Beaverlodge (Garbutt, 1964). Most of these mines operated only for a few years and all were shut down by the later 1960s. One re-opened for a short time in 1970s. Most of the mines were small operations without mechanical ventilation, the exception being Gunnar Mining Limited. Thus, there was a potential for high exposures in these mines. Eldorado was the last surviving operation in the Beaverlodge area and miners tended to gravitate towards Eldorado as the other operations shut down. The results of the unrecorded exposure of the mines is that the exposures recorded by Howe et al. (1986) likely underestimate the exposures actually received by the men.

WL and WLM Estimation

The first radon daughter measurements were done at Beaverlodge in 1954 and again in 1956 as part of surveys of radiation levels, dust and general ventilation conditions (Frost, 1983). Eventually, these initial surveys resulted in a program of radon and radon daughter measurements. The data in the 1954 survey indicate that simply turning the compressed air on or off gave rise to substantial changes in workplace concentrations. Whether a man worked in this envelope of fresh air or outside in the

"unventilated" region is thus likely to be quite important in determining his true exposure.

Early measurements were made for the purpose of providing data for ventilation control. Originally, only the Tsivoglou method was available for radon daughter measurement, but because it was complicated, most samples were analyzed for radon only (Frost, 1983). After the Kusnetz method came into use, it was applied to radon daughter measurements and an increasing proportion of the measurements were done in terms of radon daughters. By the mid 1960s, the Beaverlodge ventilation department was relying primarily on radon daughter measurements.

In 1967 Eldorado decided to start retaining personnel records of radon daughter exposure for full shift underground workers. The workers' time cards indicated the hours spent in each workplace. These were consolidated into monthly manpower working places on a computer printout. The printout, together with the measurements made in the workplace and the travelways, were used to calculate the radon exposure on a monthly basis.

In 1970 Eldorado expanded their computer system to include cumulative exposures in the summary reports. The previous totals were transferred from the cardex system to the computer. Also, during this period records of previous engineering (as opposed to dosimetry) measurements were used to assist in the back-calculation of exposures to 1 November 1966. Similarly, in 1971, maintenance, technical and supervisory personnel who received some radon daughter exposure were added to the exposure role. Their exposures were calculated using mine average WL and hours worked per year with the proportion of time spent underground.

In the mid 1970s work started on the estimation of pre-November 1966 exposure. Only radon daughter measurements were used in

this estimate thus excluding the early survey data and most of the 1950s measurements which had been for radon only. Because of the scarcity of pre-1964 data, Eldorado used an annual averaging process. Because of the variability of workplace conditions, the decision was made at that time to use the median as opposed to arithmetic mean to describe the central tendency of the exposure. Based on a review of work histories for individuals employed prior to November 1966, a system of 22 job categories was devised with classification into a particular category based on potential radon daughter exposure. Each person was assigned to a category for each job held throughout his/her employment. An effective radon daughter concentration (WL) was calculated for each job category for each year based on the fraction of working time spent in each area (e.g. underground office, etc.). These calculations (Frost, 1983, Draft #4 of the Beaverlodge WLM calculations) provide the basis for the exposure estimates in Howe et al (1986).

Subsequently, Eldorado re-examined the exposure data and attempted to make use not only of the radon daughter measurements but also of the radon samples, taking care to separate areas identified as idle from those where men were actually working. In these revised calculations, arithmetic means were used instead of geometric means or medians and the method for estimating equilibrium factors was somewhat revised. Both the earlier (Draft #4 calculations) and the current estimates involved a time split of 80% to the workplace and 20% to the travelways. The values used in the epidemiology study are compared to those recalculated by Eldorado (Frost, 1989) in Table 2.6.

Frost has tested the effect of this re-evaluation on a group of 78 miners, 28 of whom had no change in exposure since they started work after 1961. Frost calculates that the ratio of recalculated mean exposure of the 78 miners to that used by Howe

Table 2.6

ANNUAL MEAN RADON DAUGHTER CONCENTRATIONS
IN THE BEAVERLODGE MINE¹

<u>Year</u>	<u>Epidemiology</u> ²	<u>Review</u> ³
1954	6.15	26.05
1955	2.06	3.82
1956	1.06	2.81
1957	1.31	2.59
1958	0.69	1.10
1959	0.81	1.30
1960	0.84	1.75
1961	0.83	1.30

Notes:

- 1 Adapted from Frost (1989).
- 2 Data used in Howe et al. (1986).
- 3 Re-evaluated concentrations (see text).



et al. (1986) to be 2.63. If the 78 miners chosen by Frost are a random sample, this suggests that the exposures used in the epidemiological study may be too low by a factor of 2 to 3 and hence the risk coefficient would be too high by the same factor.

Howe et al. (1988 unpublished) also reported the results of a nested case control study on the same cohort of Beaverlodge miners. This study was designed to assess possible confounding from cigarette smoking and whether unreported exposures to radon daughters in other mines could have lead to an overestimate in the risk coefficient. Howe et al. (1988) conclude from the case control study that there is no confounding between smoking and radon daughter exposure and that risk coefficients estimated from the case control study are essentially identical to those estimated from the original cohort. This aspect merits further investigation.

Overall in the Beaverlodge cohort, there are 8,487 workers who were employed between 1948 and 1980 and a total of 65 lung cancer deaths were observed versus 34.24 expected. Underground miners had a mean duration of employment of 15 months, and the mean cumulative exposure of underground miners was estimated to be 16.6 WLM. As an aside, the first exposure category in this study was 0-4 WLM, with a mean 0.9 WLM. In light of current knowledge concerning normal background radiation exposures at home this lowest exposure category is likely subject to confounding by normal (nonoccupational) exposures.

2.6 Port Radium Miner Study

Open pit mining started in 1931. Underground operations were in place in 1933 and mining continued until 1940 when a decreasing radium demand lead to mine shutdown. The mine was re-opened in 1942 at government request and continued in production until 1960 when it was shut down.

Annual average ore grades in the 1940s averaged 0.5 to 1.2%, with occasional pockets of high-grade pitchblende being encountered in the 1940s.

From the start of operations until the later 1940s, there was no forced ventilation in the mine. Fans were installed sometime after 1947 and much more attention was given to improving ventilation in the 1950s.

This was the first mine in Canada where radon and radon daughter sampling was done. The first samples were taken in 1945. Initially, only radon was measured, but in the mid-1950s both radon and radon daughters were measured. The equilibrium factor between the daughters and the radon in 1957 was about 30%. It is probable that in the earlier days, with no forced ventilation, the equilibrium factor was higher.

From the available measurements and assuming a 30% equilibrium factor, Eldorado estimated that the annual average radon daughter concentrations were 77 WL in 1945, 38 WL in 1952, 10 WL in 1956 and 8 WL in 1957. Miners in the era of the natural ventilation could have accumulated 1000 WLM per year.

Recognizing that these early miners were at considerable risk from lung cancer, Eldorado sponsored a pilot epidemiological study of Port Radium workers (Grace et al., 1980). The study of Howe et al. (1987) is a follow-up to the earlier study of Grace et al.

Howe et al. (1987) also investigated a group of some 2103 miners employed between 1942 and 1960 at the Port Radium uranium mine in the NWT. In this group, 57 lung cancer deaths were observed compared to 24.73 expected.

In their paper on Port Radium miners, Howe et al. (1987) note that employment records were not available until 1940 and hence exposures before that date have not been estimated. As a consequence, the exposures of the Port Radium miners may well be underestimated and thus risk coefficients estimated from the Port Radium data should be regarded as providing upper limits.

While radon gas samples were made as early as 1945, data are sparse and the uncertainties in the exposures are likely very large. In the Port Radium study, unlike the Beaverlodge study Howe et al. (1986) used the annual average WL value to describe exposures. These authors also indicate that weighted average equilibrium factors were calculated based on the known labour distribution and type of work place. The highest factor used for many work groups was 0.5, although it was discovered according to Howe et al. in analyzing the Beaverlodge data that substantially higher values could have occurred. Working hours were based on a 40 hour week and 48 weeks per year. As noted by Howe et al. (1987) there are many potential sources of error in the radon daughter exposure estimation procedure.

Overall, it can be concluded that radon/radon daughter exposures for the Port Radium miners are highly uncertain and possibly underestimated.

2.7 Newfoundland Fluorspar Miners

The history of fluorspar mining in St. Lawrence, Nfld is briefly described in a recent report by Morrison et al. (1988). Further details on the history of fluorspar mining in St. Lawrence, Nfld. are provided in the report of the Royal Commission on Radiation Compensation and Safety at the Fluorspar Mines, St. Lawrence, Nfld. (Aylward, 1969).

The earliest mine to start operation at St. Lawrence was the Black Duck Mine which belonged to the St. Lawrence Corporation. This mine opened in March 1933. Originally, mining was by open cut methods; however, by 1937, the open cut had reach a depth of about 90 feet. According to the report of the Royal Commission, pumps could not cope with the amount of water then in the open cut and it was necessary to sink a shaft which eventually went to a depth of 250 feet. This mine ceased operations in 1942.

In 1937 the St. Lawrence Corporation started work on a vein called Iron Springs which was originally open cut but, by 1938, had moved to underground mining, eventually to a depth of 970 feet. This mine was closed in December 1956.

Practically all miners at St. Lawrence who worked underground prior to 1960 and who were employed by the St. Lawrence Corporation had at some time during their period of underground work also spent time working in the Iron Springs mines.

The report of the Royal Commission notes that the St. Lawrence Corporation had 16 veins of fluorspar on their mining properties and most of these at one time or another were mined by the company.

Morrison et al. (1988) postulate that, since operations were converted to underground mining procedures in the mid 1930s during the middle of the depression, work was done with antiquated equipment and that it was possible that health and safety conditions were poor as a result of the then existing financial situation.

According to the report of the Royal Commission, working conditions in the Black Duck mine were unpleasant. The Commission notes (page 21) that drilling was done with a dry

hammer and that dust and smoke was always so thick that one could not see the driller until you walked right up to him. "He was always like a snowman and also had to shut off his machine to clear out his eyes and nostrils." Clearly the mines were poorly ventilated and any radon brought into the mines with mine water would likely remain in the mine for a long period of time, resulting in high radon/radon daughter equilibrium conditions.

Until 1942 there were three shifts working underground at the Iron Springs mine. Late in 1942, the mine was put on two shifts. This change was most beneficial and meant that the four hours between shifts could be used for blowing out the smoke with compressed air. There was practically no forced ventilation in any of the mines up until 1960 prior to which the only source of ventilation was natural draft.

Mines were inspected annually by inspectors brought in by the Nfld. Government; however, it was not until 1951 that mining regulations were in place. The inspectors relied on persuasion only to achieve gradual improvement over the years.

Morrison et al. (1988) note that, although more than 40 fluorspar veins were located in the St. Lawrence area, most of the ore produced came from only two mines, Iron Springs and Director. These were mined by the St. Lawrence Corporation and the Nfld. Fluorspar Corporation, respectively. According to Morrison et al. (1988), the Iron Springs mine is believed to have had the worst ventilation of any mine in the St. Lawrence area. In contrast, the Director mine from 1955 onwards had some forced air ventilation. Both the Director and Iron Springs mine were extremely wet.

From the mid 1950s, it was clear that miners in St. Lawrence were suffering from various respiratory troubles, some of which had

been diagnosed as silicosis. For this reason, the Provincial Department of Mines requested the Federal Dept. of Health to carry out a survey of dust conditions in the St. Lawrence mines. Subsequently, the Industrial Hygiene Division of the Dept. of National Health and Welfare carried out a dust survey in the period 1956-1957. By the end of 1957, it was clear that the miners of St. Lawrence were suffering from a respiratory ailment that was not caused by the excessive quantities of siliceous dust. The dust survey was therefore expanded into a broader epidemiological study. By the end of 1959, Windish had completed two brief radiation surveys in the mine. Results of these surveys established that airborne radioactivity in the form of radon/radon daughters was present in the two mines surveyed in excess of the maximum permissible concentration (indicated to be 1 WL in the Royal Commission report). One of the suggestions made by Windish was that radon-222 was carried into the mine by minewater.

As described in Aylward (1969), the Occupational Health Division of the Federal Department of Health began a detailed clinical investigation of the St. Lawrence miners in August 1960 under the direction of Dr. A.J. Devilliers. Current epidemiological studies have evolved from this foundation. It should be noted that prior to 1959 there were no measurements of radon or radon daughters in the Nfld. fluorspar mines.

Based on work done by Arthur D. Little (1960, as described in the Report of the Royal Commission, e.g. p. 53, 54) the source of radon was eventually identified as the water which poured into the mines. The radon itself apparently originating from the host granite. Table II of the Report of the Royal Commission (ibid) reports levels of radon in the minewater from 300 to 13,000 pCi/l.

Interestingly, high radon levels were not limited to minewater. According to data in Table 5 of the Royal Commission Report, measurements of radon-222 in municipal water supplies in the St. Lawrence area had radon levels ranging from 1800 to 14370 pCi/L. Other water supplies also in the St. Lawrence area ranged from 6-12,000 pCi/L. Radon levels in other neighbouring communities close to St. Lawrence were found to range from 1-1140 pCi/L.

Morrison et al. (1988) note that in 1960 as a result of the high levels of radon found, mechanical ventilation was introduced into all levels of the mine still operating, and the radon daughter levels fell below 1 WL.

Prior to 1960 when additional ventilation and control measures were introduced, it was likely that miners were exposed to average radon daughter concentrations of perhaps 2.5 to 10 WL depending upon the type and place of work.

The most recent analysis of the Newfoundland fluorspar miners is that performed by Morrison et al. (1988). In this study, the cohort consists of 1772 miners employed by either the St. Lawrence Fluorspar Company or by the Newfoundland Fluorspar Limited. Morrison et al. (1988) describe the data bases, personal identifying information and occupational histories. Of particular interest here is to note that the WLM estimates used in the most recent analyses were calculated on the basis of year, mine and occupation for the period 1933-1960 based on data provided by the Atomic Energy Control Board.

The Atomic Energy Control Board calculations are those of Dory and Corkill (1984). From 1961 onward, WL and/or WLM estimates were available from the miner's individual files. In their study, Dory and Corkill review the environmental conditions in the early years of mining. Based on an assessment of

environmental conditions determined by a review of mine maps, inspectors reports, commission hearings, anecdotal information from former workers, and the authors' own experiences, exposure re-evaluations were carried out.

Comparison was also made to conditions in the mines in later years when radiation samples were available. Dory and Corkill also made use of computer modelling to simulate expected work environment conditions for each mine for each year of its operation. Most importantly, the authors recognize the uncertainty in the estimation procedure and present a range of radon daughter concentrations for various workplaces depending upon the degree of wetness and degree of mine ventilation assumed to be present in the particular workplace. Corkill and Dory (1984) note that the ranges they present do not represent extreme concentrations but are "average workplace concentrations for high, medium and low areas".

Corkill and Dory felt that it was possible to place job types within certain average concentration ranges. The exposure re-assessment carried out by Corkill and Dory substantially improved the WL and WLM estimation for the Newfoundland fluorspar miners. Notwithstanding this observation however, as in all attempts at reconstruction, there are without doubt large (and likely irreducible) uncertainties as to the actual conditions which existed in the workplaces for the period 1933 through to 1960.

2.8 Swedish Iron Ore Miner Study

Early Swedish miner data is conveniently summarized in paragraph 216 and following of Annex G of UNSCEAR (1977).

Snihs (1973) developed his risk estimate by making the important assumption that radon daughter levels in Swedish mines measured

since 1969 are representative of earlier years. Snihs (1973) made some "...qualified guesses..." as to the exposures that may have occurred and may be related to the observed mortality from lung cancer. Snihs (1981) provides further discussion of the measurements of radon and radon daughters made in Swedish non-uranium mines which were started only in the late 1960's.

In discussing Swedish mines, it should be noted that there were no radon measurements in Swedish mines prior to 1969 during which period investigations were initiated by the National Institute of Radiation Protection, Stockholm. Therefore, Swedish investigators necessarily had to perform their investigations based on reconstruction of miner exposures to radon/radon daughters. Since 1932 was the average year that underground work began, it was necessary for these authors to estimate exposure backwards in time an average of approximately 36 years.

Radford and St. Clair Renard (1984) report on a retrospective study of lung cancer mortality in a group of Swedish iron miners. In this study, lung cancer in a group of 1455 iron miners was investigated. The total cohort contained 24,083 person-years at risk with an average exposure of approximately 81.4 WLM (ibid, page 1490).

In September 1985, Swent and Chambers (1986) visited Sweden and met with several Swedish scientists, mine doctors and mining engineers. Their visit included underground examination of the iron mines at Kiruna and Malmberget. Based on their mine visits, examination of raw data and discussions with mine ventilation engineers, Swent and Chambers concluded that the exposure estimates of Radford and St. Clair Renard are likely to have been under estimated, perhaps by a factor of 2 to 3. There are several reasons for this view, but put simply these authors concluded that as ventilation conditions improved in the mines,

the exposure conditions in the mines would have improved (i.e. lowered), and hence past exposures calculated using unadjusted recent measurements (i.e. data from 1968-1972) are likely to have been underestimated.

A brief summary of some key features of the Swedish iron mining studies of Radford and St. Clair Renard are noted in Table 2.7. As suggested in Table 2.7, the assumptions of Radford and St. Clair Renard of constant exposure conditions is unlikely as a result of improving ventilation conditions which not only reduces the radon levels but also reduces the radon daughter equilibrium factor.

2.9 Overview

Based on our examination of miner data, as summarized in the foregoing (further details and references are provided in Appendices A through G) it is possible, albeit subjectively, to assess the quality the data on which the exposure estimation was performed for each of the various studies.

All the studies have some common features; namely, in all the studies some extrapolation or estimation of workplace conditions is required. Therefore, there are uncertainties associated with exposure estimates for all of the epidemiological studies beyond those associated with natural variability in workplace conditions.

Moreover, for all the studies, there are some uncertainties concerning the work histories of the miners. In some instances, miner records may have been lost from government agency files or from company files either through simple loss or misplacement, or loss associated with fire or flood. In addition, there are uncertainties concerning not only the actual working histories of

Table 2.7

SUMMARY OF KEY FACTORS FOR SWEDISH IRON MINERS

1930 NOMINAL START OF STUDY

1969 FIRST (NIRP) RADON MEASUREMENTS

TO 1973 FRESH AIR DRAWN THROUGH BROKEN ROCK
(PREHEAT)

1955 MECHANICAL VENTILATION INTRODUCED TO
REPLACE NATURAL VENTILATION

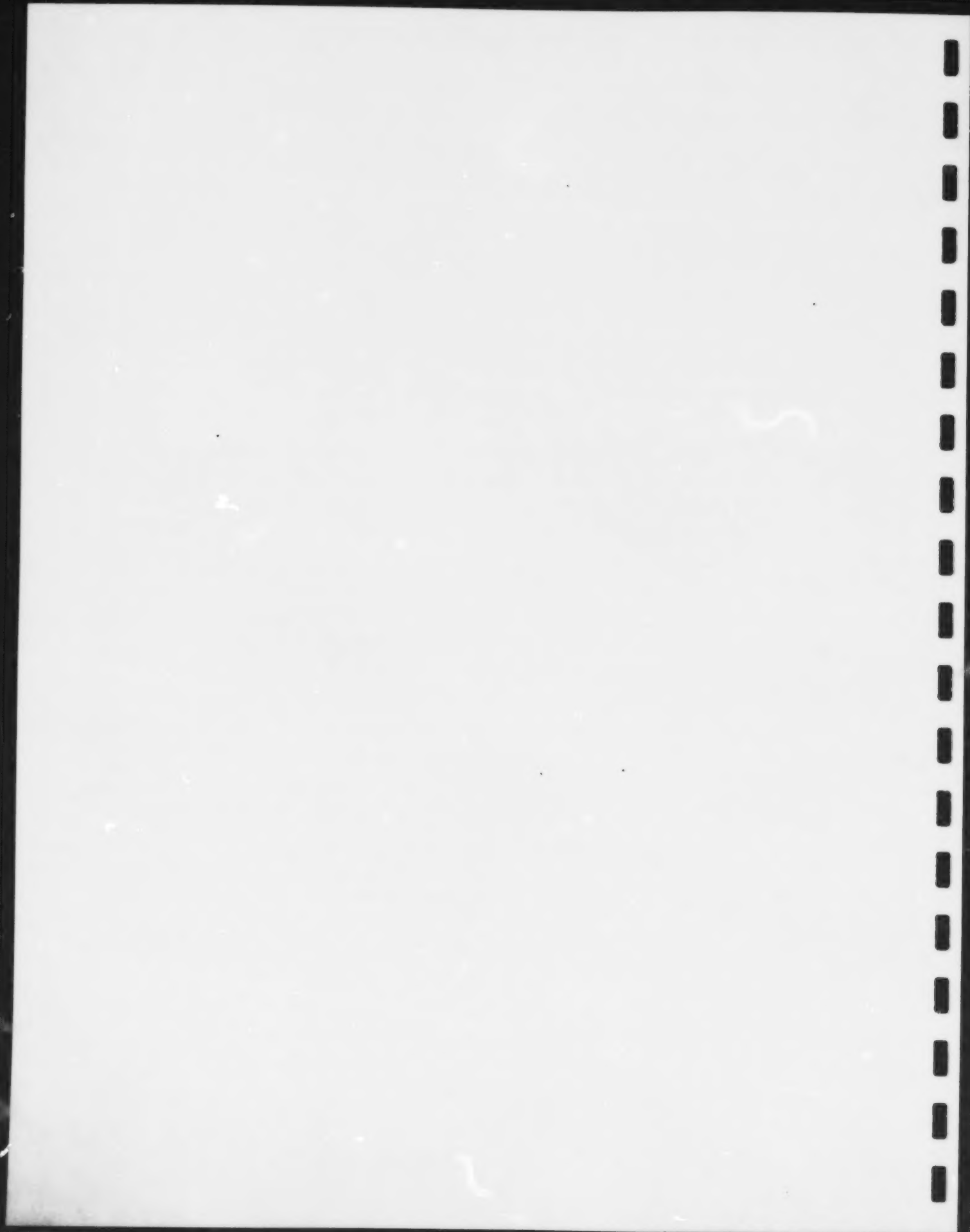
SOME AIR RECIRCULATION OCCURRED
(TO ABOUT 1965)

1965 DIESEL INTRODUCED

ALL EXPOSURES "GUESTIMATED"

RADFORD AND ST. CLAIR RENARD (1984) ASSUMED CONSTANT EXPOSURES
PRIOR TO 1968 - THIS UNLIKELY BECAUSE OF:

- CHANGING VENTILATION PRACTICE
(E.G. INCREASE OF VOLUMES AND ELIMINATION OF
RECIRCULATION)
- INTRODUCTION OF MECHANICAL VENTILATION
PRIOR TO FIRST RADON MEASUREMENT



the miners at a particular mine, but indeed about the mines in which the miners worked.

Overall it is possible, at least conceptually, to assign varying degrees of confidence (quality) to the exposure estimation procedure, in general terms:

. pre 1950 -

In practice, most mines were ventilated using natural draft ventilation. There were either no, or at best few, radon measurements and the exposure estimation must rely primarily on records of mining and ventilation practices. Data for this early period is of lowest quality and most uncertain.

. 1950 through about 1955 -

During this period because of the increasing recognition of the potential health hazards associated with radon and radon daughter exposure in uranium mines, there were increasing numbers of measurements (of radon and radon daughters) made in mines in Canada, U.S. and Europe. At the same time, attempts were made to improve mining and mining ventilation practices. In general terms, there are considerably more data than existed prior to 1950 and overall the data is likely to be of better quality and the uncertainties smaller.

. 1956 through 1966/1967 -

There was an increasing move to systematic measurements of radon and radon daughters (especially radon daughters following the recognition that the hazard was associated with radon daughters rather than radon) and increasing

attention was given to mine ventilation conditions and evaluation of exposure situations. Therefore, exposure data for this period is relatively good compared to the two previous periods.

. 1966/1967 onwards -

This might be referred to as the modern period in which there are systematic programs by companies and by government agencies to monitor and record workplace conditions and miner exposures. The data for this period is of the highest quality; however, it is also of least interest to epidemiological investigations as most of the lung cancers occur in men with exposures occurring mainly in earlier periods.

Overall, our assessment of the quality of the exposure data for the various studies is given as follows:

. highest quality -

In this category, we group the U.S. (Colorado) miner study, the Ontario miner study and the Czechoslovakian miner study. While extrapolation is required for all of these studies, considerable measurement data are available. Moreover, while the exposures estimated for these studies are uncertain, we are not aware of any systematic bias to overestimate or underestimate.

. intermediate quality -

The Beaverlodge study is included in this category since there is a possibility that the exposures may have been systematically underestimated. With a systematic re-

examination of the basis for exposure estimation, this study would be of similar quality in terms of exposure estimation to the three previously noted studies.

We also include the Newfoundland fluorspar miner study in this category. Necessarily, there is considerable reconstruction required for the Newfoundland fluorspar study. Indeed, all the exposures of interest were developed via reconstruction. However, the most recent epidemiological study made use of all the available data in an attempt to estimate WL conditions by year and by mine. This was a substantial improvement over previous studies. Notwithstanding this observation, since reconstruction is the sole basis of exposure estimation, this study is necessarily of lower quality than the foregoing mentioned studies.

. lowest quality data -

On the basis of data available, there appears to be less information available for reconstruction of exposures in the Port Radium miner study. Moreover, there is a clear recognition of some missing exposures in miners who worked prior to 1940 that may lead to a potential bias towards underestimation of exposures.

In our opinion, the lowest quality of exposure data of any of the major studies is that currently developed for the Swedish iron ore miners.

Necessarily all the exposures of interest had to be reconstructed. The authors did not attempt, to our knowledge to take account of changing mining methods and ventilation conditions and, therefore, in addition to the

uncertainty inherent in any reconstruction effort, there is also likely to be bias toward underestimation of exposure.

It is possible that a systematic re-examination of the data base available for estimation of Swedish iron ore miner exposures could be performed. In our view, it would be desirable to re-assess the exposures of Swedish iron ore miners in a fashion similar to that performed by Corkill and Dory (1984) for the Newfoundland fluorspar miners. The quality of exposure estimation for the Swedish likely could be substantially improved by such an effort.

3.0 SOURCES OF UNCERTAINTY IN EXPOSURE ESTIMATION

3.1 Introduction

Epidemiological studies of underground miners with uranium and other hard rock (OHR) experience provide the prime basis for estimating risk from exposure to radon daughters. Any uncertainty in the exposure estimation is transferred to uncertainty in the risk estimation. This chapter discusses various sources of uncertainty in the estimation of the past exposure of miners to radon daughters.

Uncertainty

A chronic difficulty in evaluating the results of epidemiological investigations is the identification of, and adjustment for, factors which may affect risk. Such factors include the characteristics of the radiation exposure itself (e.g. the total WLM exposure, or the rate of accumulation of WLM exposure); the age at start of mining; the age at occurrence of lung cancer; smoking experience; time since exposure; and whether or not the miners were exposed to other agents in the mine air which were either potentially carcinogenic themselves or which may affect the process of carcinogenesis. Incomplete specification of such factors and/or incomplete or improper allowance for the effects of such factors will certainly contribute to uncertainty about the risk coefficients derived from the epidemiological studies.

Davies (1985) provides a succinct discussion of various limitations of epidemiological studies and various factors which may affect dose response relationships. Petersen and Sever (1982) and BEIR IV (1988) also provide concise descriptions of various factors and uncertainties which affect the interpretation of epidemiological studies. While such factors are of

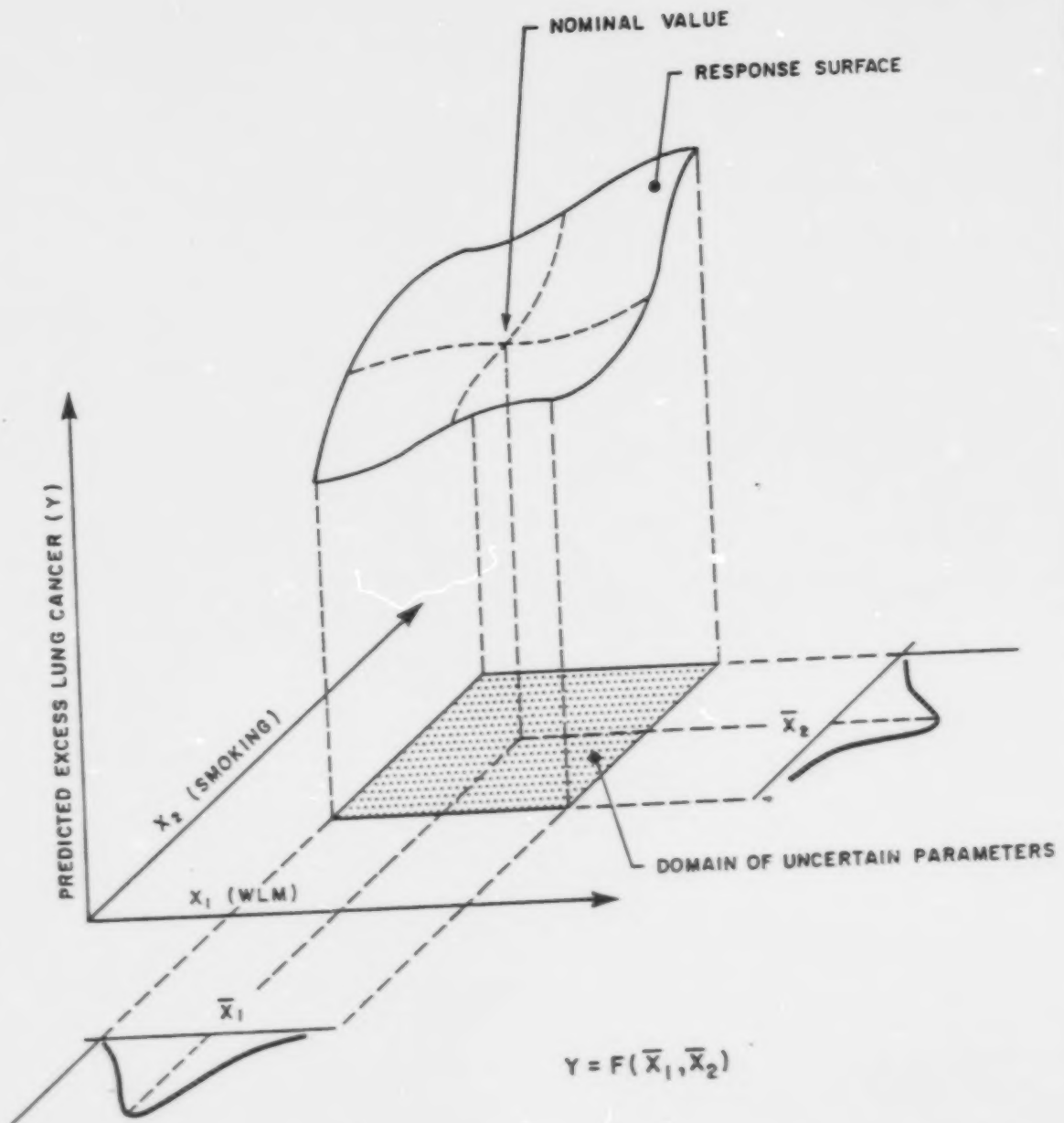
considerable technical interest, they are beyond the scope of this study which focuses on one specific factor, namely the WLM exposure variable. Indeed, in this section and subsequent sections of this report, we assume that the other factors which affect the interpretation and estimation of risks have been accounted for, at least to the maximum extent practicable. We know, however, that this is not fully correct and that lack of or imperfect correction for these factors will introduce either bias or uncertainty or both into the estimation of the risk coefficient.

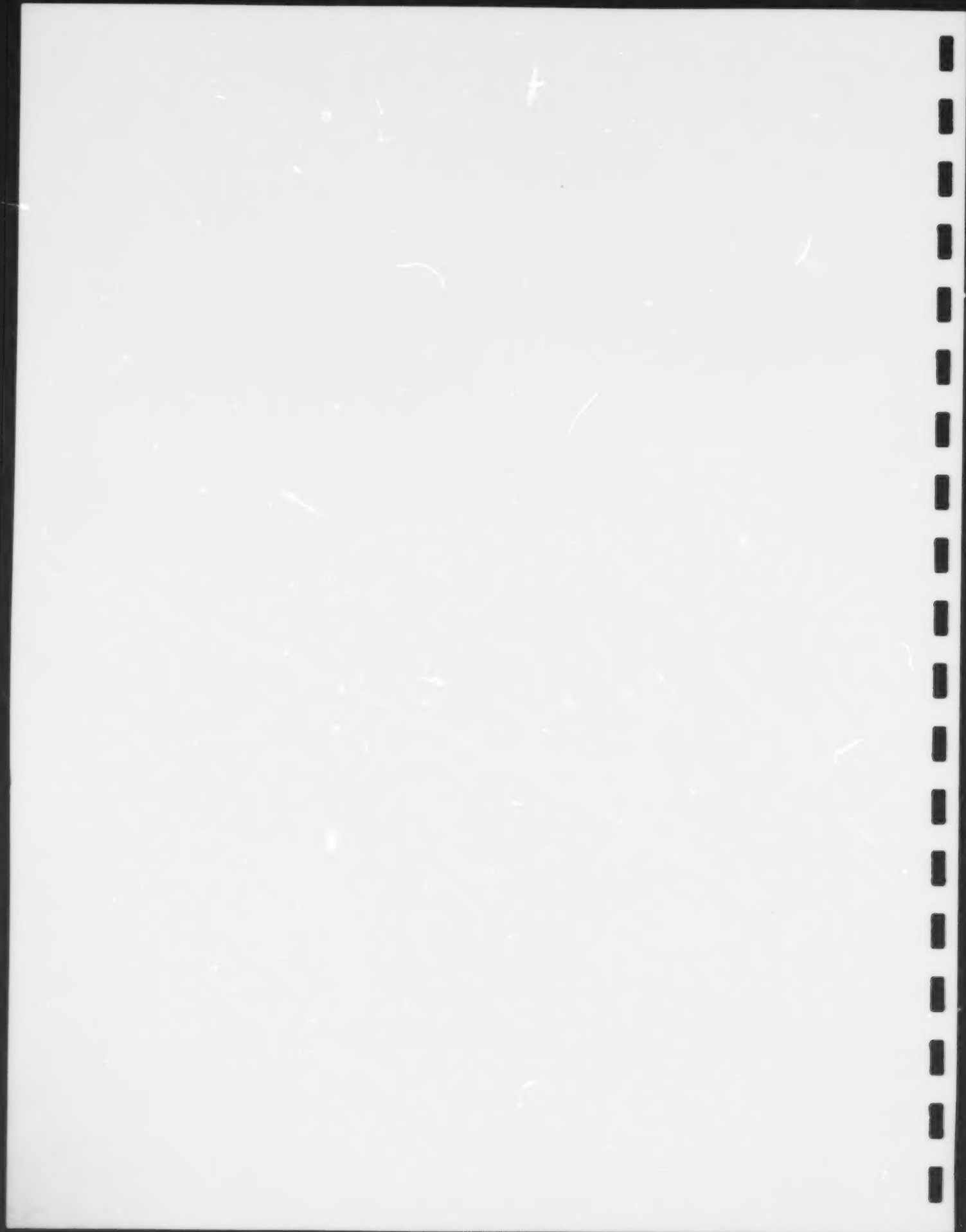
Consider Figure 3.1. In this Figure, the vertical axis represents the excess of lung cancers predicted by an epidemiological model. The X_1 axis represents the exposure variable with increasing WLM exposures progressing outwards from the origin. Similarly, the X_2 axis represents increasing smoking experience.

In the "model" illustrated on Figure 3.1, the assumption is made that all variables other than those two shown have been properly controlled for. Even presuming that we have done our very best to properly estimate the radon daughter exposure experience and the smoking experience, neither of these two variables are precisely known. For example, men who were smokers at the time of their interview may have ceased smoking; and men who were recorded as nonsmokers at the time of interview may have smoked previously. Similarly, the rate at which these men smoked may have been improperly recorded, etc.

Similarly, and for reasons discussed below, there are uncertainties about the WLM exposure of individual miners and of the total group of miners. This is represented on Figure 3.1 for a man (or a group of men) who has accumulated an average WLM exposure of $\bar{X}_1$ and an average cigarette smoking exposure of $\bar{X}_2$. The figure illustrates that there is a range of possible values

FIGURE 3.1
ILLUSTRATION OF THE ROLE
OF UNCERTAINTY IN RISK ASSESSMENT





of $\bar{X}_1$ and $\bar{X}_2$. This is reflected in the response surface. A perfectly acceptable response (according to our model) could occur anywhere within that surface. The effect of improper adjustment for factors such as age or time since exposure would be to add another level of uncertainty which would be reflected in the size and shape of the response surface. Unfortunately, in many of the studies, we don't know (or at best we are somewhat uncertain about) what effect lack of control for these variables would have.

Exposure Reconstruction Methodology

Figure 3.2 is a simplified flow sheet illustrating some of the steps and information required to estimate WLM exposure for miners. First we note that for each miner an employment history is required. This is an identification of all the mines at which a miner worked and the periods of time and years during which he worked at each mine. (Employment in non-mining experience may also be of interest if there is a potential for exposure either to radon daughters or some other lung carcinogens.)

For each employer (i.e. each mine), it is necessary to establish in as much detail as possible exactly what the miner did during his employment at that mine. Government records, company records and records of employee interviews provide the basic data for the analysis of a miner's work history.

The radiological characteristics of each workplace need to be assessed (and indeed any other characteristics of the workplace which might confound the risk assessment need to be established), preferably on a year by year basis. The various uncertainties and possible biases associated with evaluating exposures for each of the workplaces therefore also need to be considered. For example, what was the standard working day; what fraction of the

working time was spent in the workplace and what fraction of the time at work was spent in the travelways; what controls were used to limit dust generation in the early days of mining and how might these have affected the radon daughter concentration; did the miner work in the zone of clean air surrounding compressed air equipment or did he work outside this envelope...?

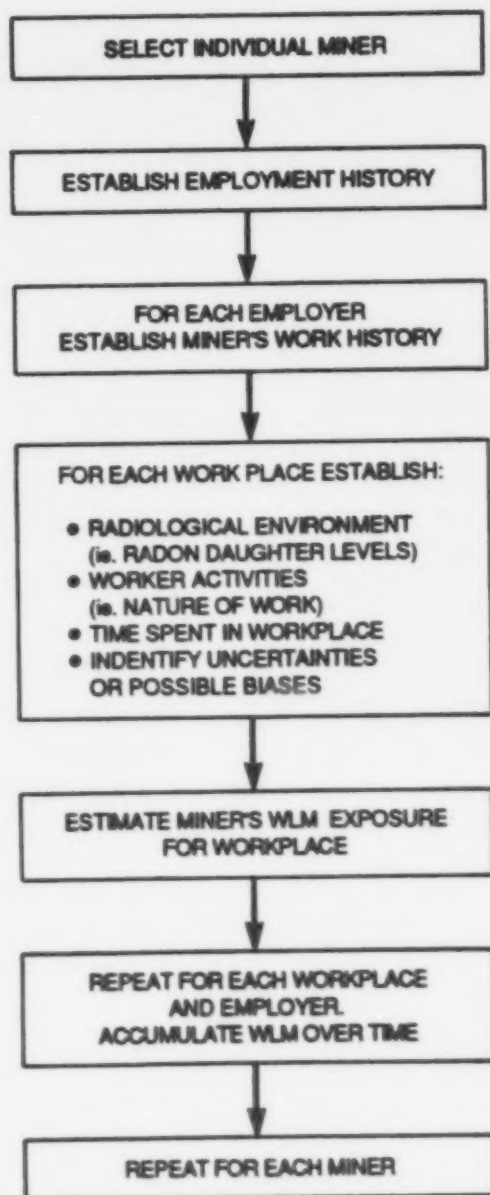
The next step in the exposure estimation process is to calculate the miner's individual WLM exposure for each workplace and for each working period (typically a year), and to repeat for each workplace in a particular mine and then for each employer (i.e. mine) over the miner's entire working history. (These analyses are sometimes complicated by the miner's mobility in moving from mine to mine.)

These analyses provide an estimate of the miner's WLM exposure at any particular time in his work history; the miner's rate of exposure; and other relevant factors such as dust exposure. In concept, this process can be repeated for each miner. In reality, study limitations most often prevent examination of individual miners or mine areas and it is necessary to estimate the exposure of particular miners or groups of miners not by estimates performed for individual workplaces but rather by mine averages (hopefully by year of employment).

In the absence of a systematic bias toward underestimating or overestimating exposure, assumptions which lead to the overestimation of one miner's exposure are likely to lead to the underestimation of a different miner's exposure. For example, if radon daughter measurements were made in the envelope of fresh air surrounding a compressed air drill in the early days, then those measurements would be appropriate for the miner operating the drill and not appropriate (i.e. too low) for miner working outside the envelope of fresh air. However, miners are not

Figure 3.2

EXPOSURE RECONSTRUCTION METHODOLOGY





rigidly located at a particular workstation and move throughout the mine, sometimes they change tasks and they move from mine to mine.

The exposures of some mine workers, for example trammer, construction crews and pipefitters would be truly averaged as these workers do move around the mine during their work. However, miners do not move in the same way. The nature of mining was for miners to work with relatively little supervision (compared to today's miners) and a system of bonus incentives was used to maintain production. The bonus system required that the mining crew work in one (or only a few) locations to facilitate the calculation of bonus based on such factors as footage advance, tons mined etc. Therefore individual workplaces (stopes or drifts) tended to be worked by the same crew(s). However, when work at this location was completed the miner (crew) would move on to a new work location. Therefore, over time the miner (crew) would work in several locations in a mine. Moreover, as noted above the miner might also move from mine to mine. Thus, some kind of natural averaging takes place. It is therefore likely that the uncertainties concerning the average exposure of the overall cohort (or a subgroup of the overall cohort) will be much less uncertain than will the estimated exposure of an individual miner. (This aspect has indeed been specifically examined by the Czechoslovakian investigators, with the results as described previously in Section 2.4.)

Notwithstanding the foregoing observation that a kind of averaging takes place, the exposure of any individual miner could be very different from the average exposure calculated for a group of miners. For statistical analysis (such as regressions) performed using average risks and exposures for classes of miners the (radon daughters) uncertainty about the exposure of an individual miner is not important. However, systematic over or

underestimation of miner exposures is important as it has potential to result in systematic over or underestimation of exposure and consequently systematic over or underestimation of risk. Furthermore, it should be noted that in some circumstances, as for example claims for workers compensation, uncertainty (and bias) about the estimation of the individual specific exposure is very important.

3.2 Radon Daughter Concentration Estimates

Dory and Corkill (1984) provide a concise description of various factors which affect radon daughter concentrations in a mine. According to Dory and Corkill, these factors include:

1. Geological Conditions

These factors include characteristics of the host rock in the ore zone material itself. In addition, however, the presence of radon in minewater is to be a crucial factor. In the case of the fluor spar mines and the Swedish iron mines, the minewater itself rather than the ore is the principal source of radon gas.

2. Mining Method

The choice of mining method can have a significant effect on radon daughter concentrations. Mining method affects not only the rate at which ore is broken (and hence at which radon is released to the air) but also the location within the mine which the ore is broken and the way ore is handled, may influence the effectiveness of workplace ventilation.

3. Ventilation

Mine ventilation and the radon source terms are the two most

important factors that govern the radon/radon daughter concentrations.

4. Work Practices

Dory and Corkill (1984) also note that the organization of the mining cycle, the distribution of mining responsibilities, the degree of mechanization, the drilling patterns, the timing of blast and entry after blast and other factors all influence either or both the magnitude of the radon daughter concentration itself and/or the exposure times.

Data Sources

Three principle sources of information for the epidemiological investigations include government records (e.g. mine inspectors record), company records (e.g. payroll, bonus etc.) and records of employee interviews.

Unfortunately, government records are subject to the same storage difficulties as are records of mining companies and can be lost through simple carelessness or by flood or fire.

In addition to the records of either government or company measurements, there are often government sponsored investigations and commissions of inquiry, as for example, the 1967 Joint Committee on Atomic Energy in the U.S. or the 1969 Royal Inquiry into Fluorspar Mines (Aylward et al., 1969) or the 1976 report of the Royal Commission on Miners in Ontario (Ham et al., 1976). These inquiries are invaluable sources of information both of a factual nature (e.g. of measurements made previously and compiled for the commission or new measurements made specifically for the inquiry) and anecdotal information based on interviews with men who worked at or inspected the mines.

Company records are perhaps the best source of information on the factors affecting workplace radiation levels. For the early years of mining prior to the institution of radon/radon daughter measurements, the companies' documentation of ventilation procedures, ventilation air flows, general information on workplace conditions, and mine maps provide an invaluable base of information. Information concerning air flows, water inflows, etc., and even anecdotal information concerning such factors is most helpful in this regard. Company records describing the mining methods, including the evolution of the mining methods, and ventilation practices with time are invaluable. Such information might include, for example, descriptions of mining methods prior to the introduction of wet drilling, dust control practices in addition to the introduction of wet drilling, and the pattern of dust levels with time. All these data can provide valuable insight as to the changing workplace and ventilation conditions over time.

Where mines under investigation continue to operate or have been taken over by a new operating company, such records are sometimes available, although in some cases records have not been kept because of lack of space or have been misplaced as a result of one or more moves. In addition, some records have been lost through inadvertent flood or in some cases fire. Clearly, the situation is more severe in the cases of mines which are no longer in operation. These considerations are important, as the exposures of interest to modern day epidemiological studies are most likely those exposures which occurred early in the miners mining career when the radon daughter levels were relatively high.

Finally, anecdotal information obtained from employees who worked in these mines can be valuable. For example, the statements in the report on the Royal Commission on Fluorspar mining of the poor visibility and the fact the miners were covered in a white dust have already been noted. Anecdotal reports concerning the large quantities of water which flowed into the various mines are also useful, at least qualitatively, in assessing the appropriateness of the exposure reconstruction. The worker's recollection of exactly where he worked and what he did at his work location can also be valuable in reviewing or indeed establishing the miners work history file.

3.3 Simulation/Modelling

Simulation of past working conditions generally provides much useful insight as to the likely range of radon daughter levels which occurred under past mining conditions.

Simulation can either be in the form of computer modelling or in the form of measurements in a stope which is ventilated and mined using techniques as similar as possible to those used in the early days. In some circumstances, combinations of modelling and reconstruction can be used effectively to extrapolate backwards in time from measurements made in modern mines to conditions which might have existed at earlier times.

There are clearly limitations of such studies. In the case of simulation studies, the mining methods or mining equipment used in the past may no longer be available. It is possible that miners asked to carry out mining operations in these simulated past conditions may consider the conditions unsafe and may not be willing to work. It is also likely that there will be considerable uncertainty about the relationship between the conditions which are being either modelled or measured today to

those that existed in the past. Questions may arise for example, about stope geometry, the ratio of the stope size to ventilation flows, uncertainty about where the men worked, and the relevance of the various measurement locations.

Dory and Corkill (1984) report results of three such recent estimation studies, one of which was an earlier report by Corkill and Dory concerning a retrospective reconstruction of radon daughter concentrations in the fluorspar mines. In this case, data measured in a 1959/1960 survey was used to "calibrate" the mathematical model. The paper by Dory and Corkill (1984) also refers to some measurements made during a test mining operation at Beaverlodge just prior to its being closed. Dory and Corkill (1984) note that "the small amount of compressed air introduced to the heading considerably reduced the radiation levels around the miner."

With regard to the Beaverlodge mine, a paper by Smith (1964) reports some results of earlier investigations of the effect of auxiliary ventilation in a drift at Beaverlodge. This study examined the effect of auxiliary ventilation on a 3,000 drift heading in waste rock. With auxiliary ventilation of 4,000 ft³/min provided to the face of a 8 ft x 8 ft drift, the radon levels measured at all locations were between 0.2 and 0.6 of one radon tolerance (Smith (1964) reports the working tolerance of radon to be 10^{-10} Ci/L on page 72 and 3×10^{-7} uCi/cm³ on page 74). With the fans not operating, there is a substantial change in conditions. Interestingly, the highest levels do not occur at either the face or the entrance to the drift, but rather in the middle of the drift. We presume that this illustrates, near the face, the effect of compressed air from the drilling, whereas near the stope entrance, we presume this reflects the influx of air from the main airway. Smith also made some other interesting observations: "Concentrations of radon/radon daughters vary

considerably in uranium mines and are difficult to forecast. Airborne radiation levels do not conform to grade of ore; some of the highest levels encountered are in waste headings. Small flows of radon-laden groundwater can be the source of very high concentrations when least expected. Concentrations of radon and its daughters change rapidly with ventilation, and even minor airflows produced by the pneumatic equipment have an appreciable effect." (Smith, 1964, p. 72).

A 1985 report (DSMA, 1985) describes the results of an attempt to reconstruct the environment that existed in the 1950s and 1960s in the Elliot Lake mines. In this study, the authors conclude that driving a pilot raise with only compressed air for ventilation represents a maximum exposure condition for miners before introduction of forced auxiliary ventilation. The attempt at reconstruction of 1950s practices in pilot raises found that compressed air provided effective dilution near the point of release and that concentrations could vary greatly depending on where they were measured. When the compressed air was turned off, concentrations rose rapidly.

The computer simulations reported by these same authors showed that 1950s raise miner received most of his exposure in the early part of the shift. The authors suggest that the group receiving the highest radon daughter exposures at the time was not the raise miners, as suggested by earlier investigations, but the stope miners.

The authors also note that, while the radon daughter concentration may have been higher by a factor of 3, the effect on exposure to quartz and uranium ore dust is much greater. "Auxiliary ventilation airflow dilutes and removes the dust released from collaring and drilling many times more rapidly than the air released from the drill. It reduces dust concentrations

during slushing both in the raise and at the slusher bench. As a result the exposures of today's raise miners to quartz and uranium ore dust is only a fraction of that to miners in the 1950s." (ibid p. 27).

As we have noted previously in Section 2.4, two ventilation incidents in Czechoslovakian mines (in 1968 and 1973) were used by Czech investigators to derive radon daughter equilibrium factors during the period of mining preceding actual routine workplace radon daughter measurements.

3.4 Some Factors Affecting The Calculation of Dose Per WLM

Discussion of the dosimetric factors which affect the lung deposition process or the estimation of absorbed dose per unit surface concentration, etc. are far beyond the scope of the present report. However, a number of factors important to dosimetry are also relevant to the present study in that they affect and therefore contribute uncertainty to the risk per WLM. Lung deposition processes are affected by factors such as particle size and unattached fraction which depend upon the nature of the mining method. Some data on dust usually may be available as a result of measurements of quartz content in the early days of mining. However, such data are often sparse, and these gross data do not provide much information on particle size distribution and radon daughter attachment fraction.

Cross et al. (1974, Appendix A) examine this aspect in some detail. These authors concur with the view that the primary basis for estimating cancer risk associated radon daughter exposure should be epidemiology. However, they emphasize that "caution is in order for interpreting such data if the exposure to the radon/radon daughter products have changed in kind from the base population chosen for the epidemiological studies" (ibid, p. A-15).

Cross et al. (1974) citing personal communication with Duncan Holaday, indicate that Holaday "has suggested that the miners were virtually exposed to the same atmosphere prior to about 1955 as after from which it could be concluded that the rads per WLM may have been essentially invariant with time" (ibid, p. A-16).

Obviously full resolution of this problem is not feasible. However, it is important for investigators when doing calculations and making statements about the rad per WLM conversion (or indeed risk per WLM estimation) to be explicit in setting forth their assumptions concerning such factors and the basis for their assumptions.

Published papers are uniformly consistent with regard to the sparsity of actual quantitative data for the early mining experience.

3.5 Radon/Radon Daughter Equilibrium Factor

It has already been noted that, for a constant source term, as ventilation conditions improve, not only will the radon concentration decline but the radon daughter equilibrium factor which depends on residence time in the mine will also decrease. Thus, there is a compounding influence of improving ventilation.

In some instances, studies have attempted to take account of this. For example, the Czechs have made use of the two ventilation accidents to estimate radon/radon daughter equilibrium factors for early mining conditions, for which period they had radon measurements but no radon daughter measurements (see Section 2.4). This approach was clearly different, however, from that of the Swedish investigators who assumed "reconstruction of exposure data by this method depends on the assumption that ventilation conditions in 1968 - 1972 were not

greatly different from those in the past" (Radford and St. Clair Renard, 1984, p. 1486).

The effect of compounding can easily be illustrated by assuming: constant physical dimensions; constant radon influx; and increasing air ventilation flows. The assumption of a constant ventilated volume is likely to overestimate the effectiveness of the past ventilation practice as it is a relatively modern practice (tendency) to isolate the working area of the mine so that, while the total volume of the mine increases, the ventilated area or the working area of the mine remains roughly constant. More typically, as the mine volume expanded, the ventilation would deteriorate until it became unacceptable and then corrective action would be taken.

According to Evans (1969, p. 242), the radon daughter ingrowth from 100 pCi/L of initially pure radon is given approximately by:

$$WL = 0.023 t^{0.85} \quad (3.1)$$

where t is in minutes.

Consider, for example, a hypothetical situation where, for example, the radon levels decreased by say a factor of five. If we (conservatively) assume fixed ventilated volumes, a two-fold decrease in radon level implies an approximately two-fold increase in airflow rate and hence, for fixed cross-sectional dimensions, a two-fold increase in air velocity. Therefore, the residence time in the better ventilated mine is approximately one-half of the time in the older mine. Taking account of the two-fold decrease in radon levels and the approximate two-fold decrease in the equilibrium factor (from equation 3.1) because of the lower residence time, we calculate that the mean WL in the better ventilated mine is about 4 times the WL value in the

older mine, not 2 times. This calculation highlights the desirability of estimating exposure conditions on a year-by-year basis using year-by-year data to the maximum extent feasible.

Clearly, for studies such as the Newfoundland fluorspar miners and the Swedish iron-ore miners, this can only be done by extrapolation as there are no radon/radon daughter measurements for the periods of interest. In the Czech mines, radon measurements exist from the earliest period of modern mining (1948). Similarly, in the U.S. uranium mines (at least some) radon measurements exist from 1949 onwards. In Beaverlodge, some radon/radon daughter measurements exist at least from 1954 onwards. Similarly, radiation measurements exist for the Elliot Lake mines as early as 1955. Thus in studies of these miners, while data for individual mine locations and indeed, in some cases, individual miner may be sparse or nonexistent, there are at least data for similar mining situations for the same time periods in the same mining regions which can be used in exposure reconstruction efforts.

An example may help to illustrate the kinds of calculations that can be done when actual data are available, such as the 1954 radon/radon daughter data for Beaverlodge.

Some summary statistics for the 1954 Beaverlodge data are shown in Figure 3.3. These data specifically exclude those areas that were indicated as idle and therefore not occupied by miners. Part A of Figure 3.3 shows the WL values for paired radon and WL measurements, 24 in total. Part B of Figure 3.3 shows the results of the 1954 radon measurements (76 measurements in non-idle areas). The difference between the median radon value and the mean radon value is roughly a factor of 3.

Figure 3.4 shows a linear regression of WL versus radon for the

paired 1954 data. The slope of the linear regression provides an estimate of the radon daughter equilibrium factor which we calculate to be approximately 0.84. This equilibrium factor when applied to the mean radon value shown in Figure 3.3 leads to a mean radon daughter concentration of approximately 32.3 WL. This is somewhat lower than the mean value for the paired radon daughter samples which reflects most likely the fact that the measurements were made in different locations and conditions. (It should be recognized that it is unlikely that the equilibrium factors will be uniform throughout the mine.)

When measurements are separated into workplace and travelway locations, it is seen that the radon concentrations in the travelway are somewhat higher than those in the workplace. This perhaps reflects the effect of compressed air from pneumatic equipment on local workplace conditions. Specifically, while the overall mean radon level is approximately 3800 pCi/L, the mean workplace level is 3530 pCi/L versus 4496 pCi/L for the travelways, a difference of about 30%.

A mine average WL value can also be calculated assuming that the fraction of the time spent in the travelway was 20%, and the fraction of time spent in the workplace was 80%. An examination of the graphs on Figure 3.3 suggest lognormal behaviour for the data. A lognormal distribution of radon levels (characterized by geometric means and standard deviations of 950 and 6.2 for the workplace (Rn_W) and 2270 and 2.99 for the travelways (Rn_T), respectively) was assumed. It was also assumed that the equilibrium factor (F) could be represented by a triangular distribution with a minimum of 0.7, a maximum of 0.97 and a mode of 0.84. Some uncertainty about the fraction of time spent in the workplace was also assumed. The fraction of time spent in the travelway (f_t) was assumed to be a triangular distribution (mode of 0.2 with a minimum of 0.1 and a maximum of 0.3). This

FIGURE 3.3
1984 BEAVERLODGE DATA
(EXCLUDING IDLE AREAS)

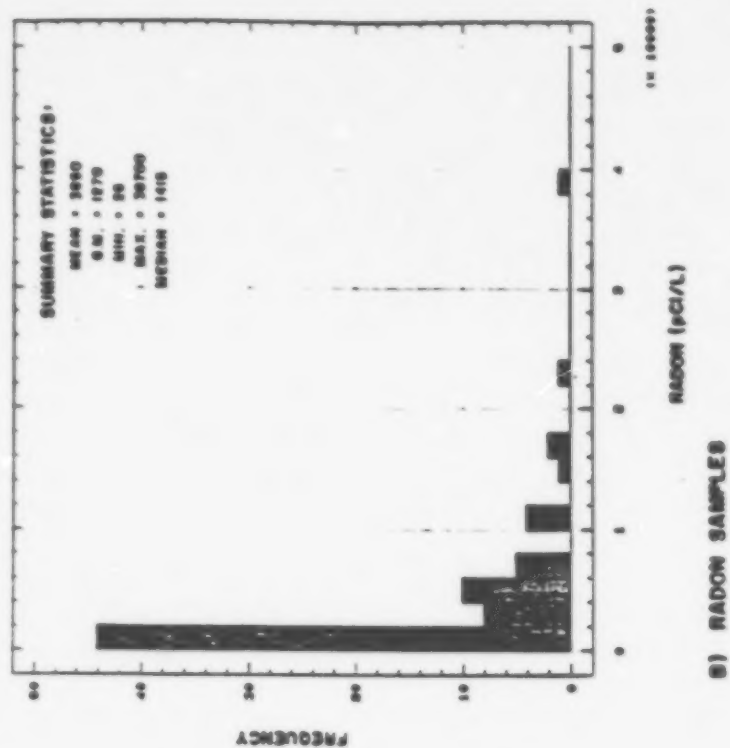
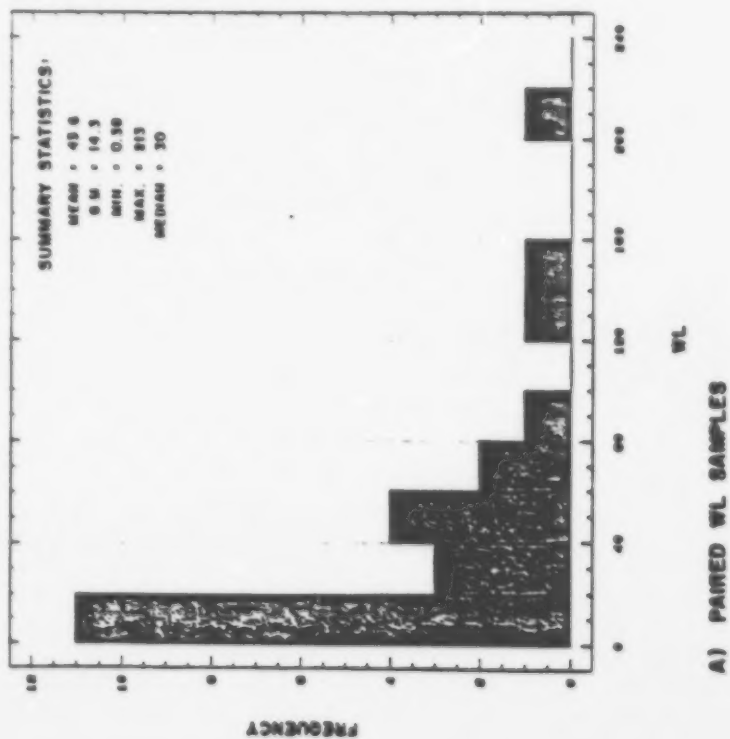
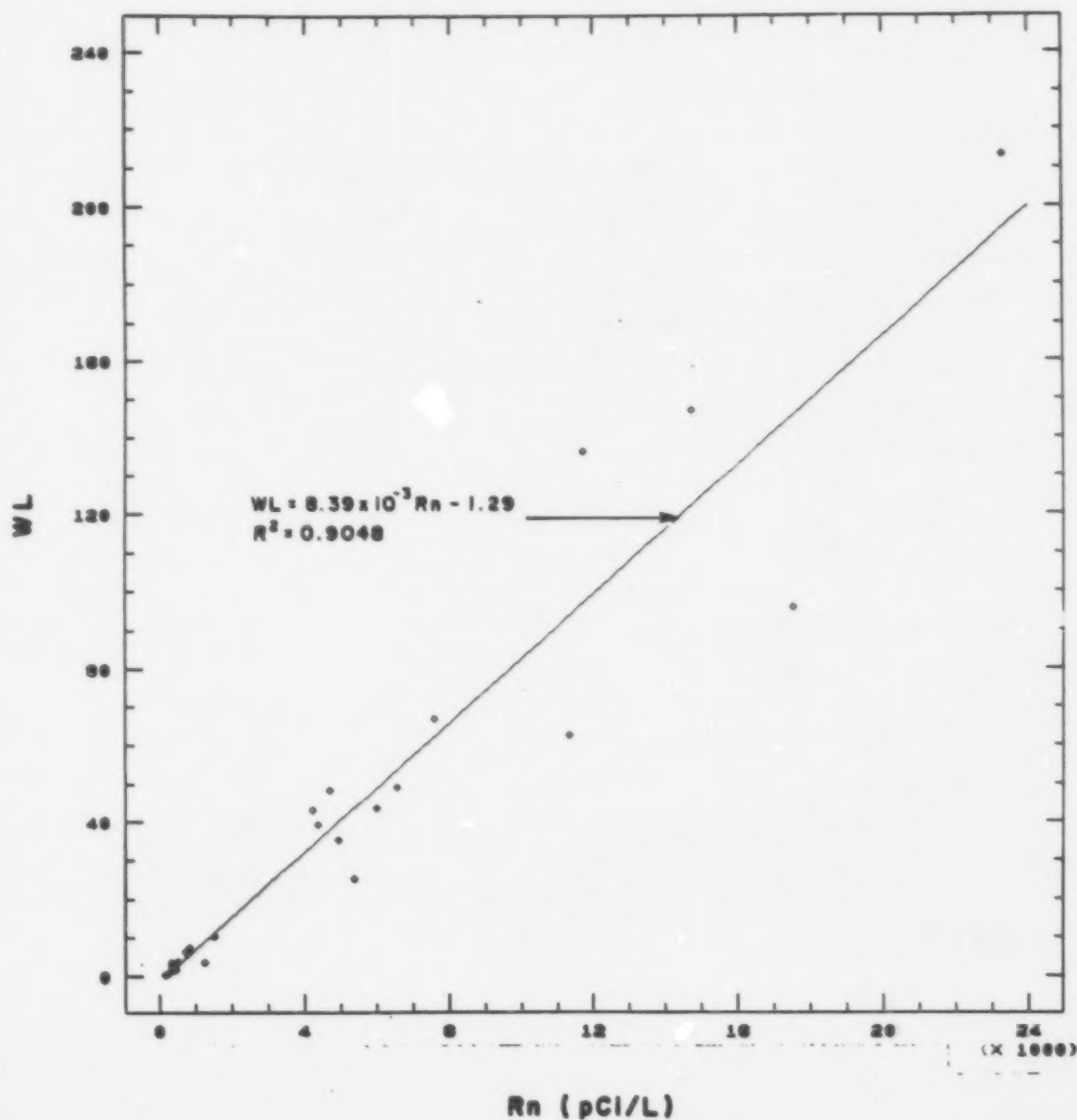


FIGURE 3.4

ESTIMATION OF "F" FACTOR FOR BEAVERLODGE
(1954)



NOTE:

1. REGRESSION LINE CALCULATED USING LEAST SQUARES METHOD AND 24 PAIRED R_n AND WL VALUES
2. BASED ON SLOPE OF REGRESSION LINE $F \approx 0.84$

latter distribution is perhaps not unreasonable as early in the mine development the length of time spent going to work would be shorter than it would be later in the mine development, when the travelways are longer. These values were used in a Monte Carlo simulation and a mine wide radon level was calculated using:

$$WL = F [Rn_T f_t + Rn_W (1 - f_t)]/100 \quad (3.2)$$

A mine wide mean value of 41.5 WL with standard deviation of 106 WL was estimated. The median value was estimated at 13.5 WL while the geometric mean was estimated at 15.1 WL with a geometric standard deviation of 3.6.

The paper by Howe et al. (1986) used median WL values. Draft #4 of the Beaverlodge WLM calculations (Frost, 1983) indicates that a radon daughter level of 6.15 was the highest WL value used for 1954 in the 1986 study of Howe et al. The foregoing calculations, albeit preliminary in nature, suggest that the WL value for 1954 used in the study of Howe et al. may be too small, by a factor of six or so, if average values are the most appropriate values to use and by a factor of two or so if the geometric mean or median is the most appropriate descriptor. Clearly this aspect requires further investigation. (It should also be noted that the differences between calculations of the type just described above and those reported in Draft #4 are likely to become relatively smaller as we move forward in time and are likely inconsequential by the early 1960s.)

One final observation is perhaps worthwhile. Samples of Beaverlodge data shown above are clearly suggestive of lognormal behaviour. Thus if one is interested in the chance of being exposed to levels in excess of a specified level, then the use of percentiles derived from the appropriate lognormal distribution are appropriate. However, if one is interested in exposure of a

miner to the work environment, the time integral concentration is of interest. This is proportional to the average value since the time integral of the time varying concentration is equal to the average concentration times the time over which the integration is performed. (It is recognized that in complex models, e.g. linear log models, descriptors other than average might be appropriate; however, such descriptors are model dependent. A discussion of these aspects is beyond the present study, however, the reader interested in this aspect is referred to papers such as that of Seixas et al. (1988)).

3.6 Work Histories

The difficulties of evaluating a miner's work history have already been noted. Even where there are good records of miner's work histories, it is not always clear that proper consideration has been given to either overtime or time off, the first factor leading to underestimation of exposure, the second leading to the overestimation of exposure. Perhaps in the absence of conscious systematic bias, this factor may not be too important for the group as a whole, but could be extremely important for individual miners (as for example, in a compensation case).

An example may help illustrate how important work history can be to exposure estimation. Figure 3.5 is based on the work history of an Elliot Lake miner. According to the miner's work history file, he worked on six different occasions in various occupations in Elliot Lake uranium mines. Nominal reported occupations and exposure hours are shown in Figure 3.5 as are both the average standard WL value and special WL values for the appropriate mines extracted from a report of Muller et al. (1983).

The graph on the left hand side of Figure 3.5 shows cumulative WLM on the vertical axis versus work period on the horizontal

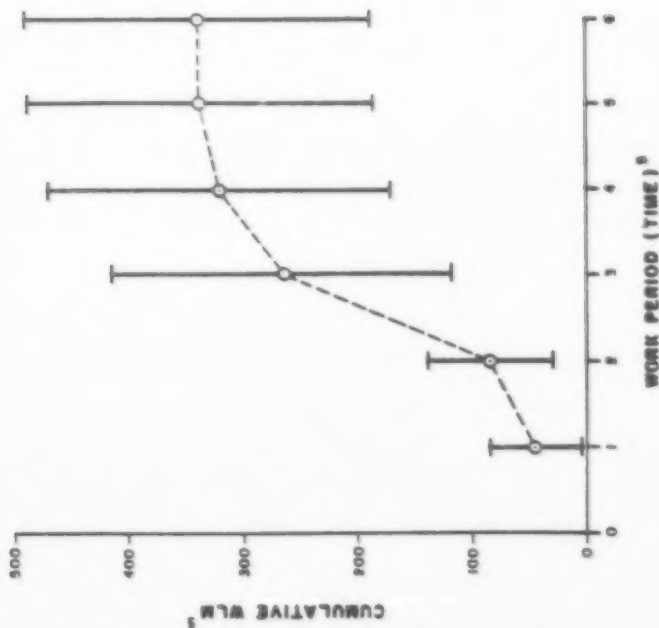
FIGURE 3.5
EXAMPLE ILLUSTRATING EFFECT OF WORK HISTORY
ON ACCUMULATION OF WLM EXPOSURE

WORK HISTORY DATA:

WORK PERIOD	REPORTED NOMINAL OCCUPATION ¹	REPORTED EXPOSURE HOURS ²	AVERAGE WL ESTIMATES ³ STANDARD SPECIAL
1	SAMPLER	4080	0.7 2.4
2	SAMPLER	1875	1.3 4.5
3	MINE-SERVICE ⁴	5700	3.1 8.4
4	MINER	3825	1.2 3.0
5	MINER	4200	0.9 0.7
6	MINER	400	0.3 0.7

NOTE:

1. COULD BE DIFFERENT JOB IN SAME MINE OR A JOB IN A DIFFERENT MINE
2. MONTHS CALCULATED AS HOURS ÷ 170
3. STANDARD AND SPECIAL WL'S AFTER MULLER et al 1975
4. MINE SERVICE INCLUDES: UNDERGROUND CONSTRUCTION, LEACHING, SHUTTLE CAR OPERATION, ETC.
5. BASED ON 1000 TRIALS ASSUMING UNIFORM DISTRIBUTION (1.0 STANDARD, 1.4 SPECIAL)



LEGEND:





axis. (Work period here is a surrogate for time; however, work periods do not actually necessarily run consecutively from one period to the next.)

The curve was calculated as follows. Workplace conditions are variable from mine area to mine area and from time to time. In view of this, Muller and his co-workers (1983) developed both standard WL estimates and special WL estimates intended to bracket the actual exposure conditions. Muller et al. (1983) suggest that the standard WL estimate is perhaps the best estimate whereas the special may be on the high side. Whether or not this is the situation is of course unclear as the measurement frequency was low and the use of the lowest of the measurements indicated does not demonstrate that a lower measurement is not feasible. Similarly, it is possible that measurements higher than those actually recorded could have been found. In view of this, we arbitrarily broadened the distribution of uncertainty about the actual WL conditions in the workplace by assuming that the "actual" WL value was somewhere between 60% of the standard WL value and 140% of the special WL value.

Using this uncertainty range and using Monte Carlo methods, we calculated exposure for this Elliot Lake miner. The data shown on Figure 3.5 is based on 1000 Monte Carlo trials. The circle is the arithmetic mean value of 1000 trials, and the bars represent the 95% confidence interval about the mean. A cursory examination of the graph indicates that if the work history file had been deficient with regard to any of categories 1, 2, 4, 5 or 6, this would have had very little effect on the final WLM value assigned to the miner. On the other hand, roughly two thirds of the miner's total exposure was associated with work period 3 when he was performing mine service duties. Therefore, if somehow or other this function had been inadvertently omitted from the miners work history, it would have resulted in a substantial

error in his assigned total WLM exposure.

3.7 OHR Exposure

The effect of OHR (other hard rock) mining exposure on various epidemiological studies has already been noted. The effect is particularly evident in the Ontario study where there are differences between the uranium miners cohort with previous gold mining experience and the cohort without gold mining experience. Therefore, it seems logical that, where the study is of sufficient size, the groups of miners with essentially pure (e.g. uranium only) experience and those with mixed uranium and other mining experience should be segregated and analysed separately. This would help to control for confounding associated with the work experience in other underground hard rock mines, including but not limited to radon daughter exposures in these mines.

While some examples of the influence of OHR mining have already been noted, one further illustration may help us to understand why OHR experience is important. The following example also helps explain the importance of work history records and work history reconstruction.

As a consequence of responding to Saskatchewan Workers Compensation Board requests, Eldorado has reviewed several work history files for various of their miners. In each case, work history files as recorded on the epidemiology master file (i.e. the file used in the analyses of Howe *et al.*, 1986) were compared to that developed through their own review.

The Eldorado review was based on their own worker files, personal interviews by the Saskatchewan Workers Compensation Board, and the records of the Saskatchewan Workers Compensation Board. The results of four such comparisons are shown on Table 3.1. The

Table 3.1

COMPARISON OF WORK HISTORY FILES FROM EPIDEMIOLOGY STUDY AND ELDORADO RECORDS

Epidemiology

Eldorado Personnel File

Miner A

Hired - miner September 1953
Quit October 1953
Exposure 1953 - 5.5 WLM

Hired shaft crew (sinking) 1 Nov/49
Quit 21 Mar/50
Fired - trackman 28 Sept/50
Quit 21 Dec/50
Rehired - miner 1 Sept./53
- AWOL 25 Sept./53

Miner B

Hired - Port Radium miner 1 November 1949
Quit 23 March 1950
Rehired 28 September 1950
Quit 2 January 1951

Exposure 1949 - 37.8 WLM
1950 - 102.6 WLM

No non-Eldorado experience

UG exposure 1949 - 500 h
1950 - 640 h
1950 - 792 h
1953 - 152 h

1953-54 Gunnar Mine - uranium
Has never worked at Port Radium.

Epidemiology file match identified worker as former Port Radium employee. He was therefore rejected from the Howe study.

Should have been retained in Howe study as live miner with substantial exposure.

Table 3.1, continued

Epidemiology

Miner C

Hired - miner Sept/61
Quit 1971
Hired - partime underground - Sept/61
Still employed - 31 Dec/80
(end of study)

(This means he was fulltime in
2 jobs - 1961-1971))

Exposure	1961 - 4.204 WLM	
1962 - 14.400 WLM		
1963 - 16.152 WLM		
1964 - 17.952 WLM		
1965 - 16.656 WLM		
1966 - 16.656 WLM		
1967 - 4.440 WLM	)	From 1967 on,
1968 - 2.500 WLM	)	exposures
1969 - 1.700 WLM	)	should be
1970 - 2.200 WLM	)	accurate
1971 - 0.500 WLM	)	
1972 - 0.300 WLM	)	
1973 - 0.800 WLM	)	
1974 - 0.700 WLM	)	
1975 - -- WLM	)	
1976 - -- WLM	)	
1977 - 1.150 WLM	)	
1978 - 1.690 WLM	)	
1979 - 0.970 WLM	)	
1980 - 0.850 WLM	)	

No other mining.

Eldorado Personnel File

Hired - miner 6 Dec/56
Quit 29 May/57
Rehired - miner 1 Mar/58
Quit - 17 June/60
Rehired - various underground
jobs - 21 Sept/61

Transferred to Safety Dept.
31 May/71. Part-time underground
thereafter.

1955-56 Nesbitt Labine Mines -
Uranium City - uranium
1957-58 thought to have worked
at Lake Cinch Uranium Mine,
Uranium City.

Probably worked in uranium
1960-61 as 1961 hire was in
Uranium City - not outside.

Table 3.1, continued

Epidemiology

Miner D

Hired - miner - July/62
 Quit Aug/65
 Exposure - 1962 - 5.060 WLM
 1963 - 20.442 WLM
 1964 - 13.542 WLM
 1965 - 6.781 WLM

No other mining

Eldorado Personnel File

Hired - drift miner - 6 July/62
 Quit - 3 Aug/65

Sept/55-Jan/57 - Stope miner,
 San Antonio Gold, Bissett, Man.

Feb/57-June/57 - Drift miner,
 Norwest Can. Dev., Red Lake, Ont.
 (cannot identify - likely gold)

June/57-Mar/58 - Drift and raise
 miner, Patrick Harrison,
 Moak Lake, Man.

Mar. 6/58-July/62 - Drift miner -
 San Antonio Gold, Bissett, Man.

Returned to Bissett, Man.
 after quit; presumably to
 San Antonio Gold?



left hand column reflects work histories as recorded on the epidemiology file, whereas the right hand column shows that extracted developed by Eldorado.

While this is only a very limited sample (indeed a biased sample since examples are all lung cancer cases), it is clear that the epidemiological record is incomplete. The comparisons suggest that miners may have unrecorded mining experience, which as noted previously, has the potential to influence the risks derived from the Beaverlodge study.

3.8 Uncertainties Today

Schiager *et al.* (1981) have examined the uncertainties in estimating WLM exposures under modern day conditions. These authors investigated 12 grab sampling methods for measuring airborne radon daughter concentrations with respect to the contributions of uncertainty which contribute to the overall uncertainty. They identified six primary sources of uncertainty, which include natural variations of airborne radon daughter concentrations, inherent measurement precision due to counting statistics (depending on concentration), human mistakes, estimation of occupancy time, record keeping and data transcription. These authors estimate an overall uncertainty range of 37-41% of which roughly 36% is attributable to the natural variation of radon daughter levels.

In principle, personal alpha dosimetry (PAD) could improve the estimation of miners' exposure to radon daughters by providing direct integration over varying workplace conditions. The Atomic Energy Control Board has been investigating the use of PADs since 1976. Balint and Viljoen (1988), in reporting on these investigations, conclude that to date "...there is a discrepancy between area sampling and PAD results. Practical Canadian

experience indicates that both the CEA and alphanuclear PADs most often read lower than the conventional area monitoring results" (ibid, p. 20).

As uncertainties in the standard grab sampling, time-weighted average approach are (only) in the order of 40%, it is not yet clear how much actual improvement in assessment of miners' exposures would be provided by universal use of PADs. This aspect should be reviewed on a periodic basis.

4.0 THE EFFECT OF UNCERTAINTY ON RISK ESTIMATES

In previous Chapters we have seen that there are considerable uncertainties in the radon daughter exposures which have been estimated for individual miners and for groups of miners in all of the reported epidemiological investigations. For reasons described previously, the quality of the exposure reconstruction is better in some studies than in others.

In general terms, the quality of the data improves as we move forward in time. In the early days of mining, there were few, if any, measurements of radon or radon daughters on which to base exposure estimates. All studies therefore require varying degrees of interpolation or extrapolation, and numerous assumptions about workplace conditions and the length of time the miners spent in the workplaces, all of which contribute uncertainty to the estimated exposures. In three of the studies examined (Beaverlodge, Port Radium and Malmberget miners), there is likely to have been a bias to underestimation of exposure and hence overestimation of risk. Otherwise, our review suggests that, while the estimated WLM exposures are uncertain, there does not appear to be any systematic bias in the estimation of the miners' past exposure to radon daughters.

In this Chapter we introduce two approaches to incorporating uncertainty in the risk estimation process. The first approach requires only the number of cases and an estimate of the cumulative WLM exposure of a group of miners, while the second approach, based on linear regression, requires stratification of risk by level of exposure.

4.2 Approaches to Incorporating Uncertainty in Risk Estimation

4.2.1 A Cumulative WLM Approach

In this approach Bayesian methods are used to evaluate the effect of uncertainty about the miners' cumulative WLM exposure on the risk coefficient. The technique requires only an estimate of the cumulative WLM exposure of the entire group of miners (cases and non-cases), and an estimate of the numbers of lung cancers attributable to that exposure. Such data are usually reasonably available from published studies. The technique allows the investigator to make assumptions about the characteristics of the uncertainty associated with the cumulative WLM exposure. It should be noted this technique implicitly assumes that the relation between the attributable risk and increasing WLM is a linear, no-threshold relation.

The basic concept is as follows. A specific group of miners (e.g. U.S. miners with only uranium experience) which has been followed for a specific time period, will have an observed number of lung cancers (k) and a calculable expected number of lung cancers (λ , lambda). The observed number can realistically be considered to result from a Poisson process. The probability distribution for K is given by:

$$p(k) = \Pr(K=k) = \frac{\lambda^k e^{-\lambda}}{k!}, \quad k = 0, 1, 2, \dots \quad (4.1)$$

If under similar conditions, however, k lung cancers have been observed, using Bayes theorem we can write the posterior probability density for lambda as:

$$Df(\lambda | k) \approx \pi(\lambda) \lambda^k e^{-k} \quad 0 < \lambda < \infty \quad (4.2)$$

where $\pi(\lambda)$ is the prior distribution for λ .

If we assume a uniform prior for λ , that is we have no reason to prefer one value of λ over another within a range of possible values the posterior probability density function for can be written as:

$$Df(\lambda | k) = f(\lambda) = \frac{\lambda^k e^{-\lambda}}{k!} \quad \lambda > 0, k \text{ integer} \quad (4.3)$$

With the standardizing constant, $f(\lambda)$ in (4.3) has the same form as $p(k)$ in (4.1). However, p sums to 1 over k while f integrates to 1 over λ .

Suppose now we postulate that $\lambda = \tilde{\lambda} W$, where $\tilde{\lambda}$ is the attributable risk of lung cancer per WLM of aggregate exposure in the group and W is the aggregate exposure of the group in WLM. If W is a random variable with a known probability distribution $Df(W)$ equation (4.3) can be transformed to obtain the following posterior distribution of $\tilde{\lambda}$.

$$Df(\tilde{\lambda} | k) = \int_W Df(\tilde{\lambda} | k, W) Df(W) dW \quad (4.4)$$

In this situation the assumption of uniform prior for λ still applies.

Specific examples of this method are provided in Chapter 5 and in Appendix I. Appendix I also describes procedures for implementing the approach for several distributions of uncertainty about cumulative WLM, namely uniform, triangular and normal distributions.

4.2.2 Regression Model Approach

Various sources of uncertainty about the miners' WLM exposure have been discussed elsewhere in this report. The fact this uncertainty about the exposure exists has important implications. This is so because, as described in Appendix H, normal regression techniques assume that the independent variable (here WLM) is precisely known. In Appendix H, an error-in-variables model (EVM) is developed which relaxes this restriction.

The technique described in Appendix H can be applied to either data for a whole study stratified according to exposure level, or to a subgroup such as uranium miners with no other hard rock (OHR) mining experience, at least where the subgroup is of reasonable size.

Published data on risks of lung cancer in (uranium) miners would typically include observed and expected numbers of cases by exposure category, person-years for each exposure category, and the numbers of miners in each exposure category. In addition, an average (or nominal) exposure is given for each exposure category and a standard deviation about the average exposure can be calculated for each category according to the prescriptions given below or directly from raw data where it is available.

Risk Models

Two empirical models are typically used to explain the excess risk caused by the radon daughter exposure. The absolute risk model is:

$$\left[\frac{O - E}{\text{PYR}} \right] \times 10^6 = \alpha_1 + \alpha_2 \bar{X} \quad (4.5)$$

while an alternative model, the relative risk model, is

$$\left[\frac{O - E}{E} \right] \times 100 = \beta_1 + \beta_2 \bar{X} \quad (4.6)$$

In both of the above relations, O is the observed number of lung cancer cases in an exposed group of miners in a given time period, E is the expected number in the same period, PYR is the number of person-years of exposure in the group being considered, and $\bar{X}$ is the average intensity of exposure in the group, measured in working level months.

When the left-hand sides of (Eq. 4.5) and (Eq. 4.6) are plotted against $\bar{X}$, straight lines result, having intercepts α_1 , and β_1 , and slopes α_2 and β_2 . It is important to use the available data to obtain estimates of these coefficients which are as good as possible. Of particular interest are estimates of the slopes (α_2 and β_2), which, in fact, are the risk coefficients.

It is useful to obtain the best possible estimates of these coefficients in the form of a single value for each coefficient. It is essential, however, that some means be exploited to assess how close these estimates are likely to be to the corresponding true values. This is the problem addressed in Appendix H. The EVM method described in Appendix H yields both point and interval estimates for the coefficients.

In most cases where straight lines are fitted to data, the method of least squares is used. In order to justify this method, it is necessary to make several assumptions, including the requirement that the observations on the independent variable perfectly represent the true values i.e. are known without error. In fitting a straight line using the method of least squares, each

observation must be perfectly described by the mathematical model:

$$y_i = \theta_1^* + \theta_2^* x_i + \epsilon_i; i = 1, 2, \dots, n \quad (4.7)$$

where θ_1^* and θ_2^* are the true values (in the real world always more or less unknown to the observer) of the intercept and slope); x_i and y_i are the observed coordinates of the i th among n data points; ϵ_i is an error which represents all of the imperfection or lack of knowledge about the exact values of y_i . The method of least squares also assumes that the x_i are known without error. In addition, the expected value of ϵ_i is zero.

Where confidence intervals for the parameters are to be calculated, it is necessary to make some assumption as to the form of the distributions of the ϵ_i . Almost invariably, it is assumed that the ϵ_i are distributed normally. In the circumstance where the ϵ_i are distributed normally, the least squares estimates are identical to the maximum likelihood estimates. In the EVM described in Appendix H, it is assumed that uncertainty exists about the true value of the independent variable x_i . The EVM technique uses Bayesian methods to explicitly incorporate uncertainty about the independent variable, here WLM, in the regression analysis. The EVM technique also allows for a Poisson distribution of cases.

The results of applying the EVM regression technique to various miner data sets are given in Section 4.3. The EVM technique permits the calculation of marginal (posterior) probability density functions for both slope (risk) and response at arbitrarily selected WLM values.

Treatment of Uncertainty in Exposure Data

- (i) When only the exposure category is known.

When it is desired to quantify the uncertainty in exposure data of this type, it is most useful to express it in terms of variance or standard deviation. When the range of values covering a particular category is known, it is usually best to assume the exposure for an individual miner to be that of a cell midpoint with an associated variance equal to $w^2/12$, where (w) is the category width in exposure units (WLM).

The use of the midpoint is justified by its minimum mean squared error property. The variance as suggested above is that of a continuous random variable which is uniformly distributed over the range w (less than infinity). A theoretical justification for the uniform distribution is that it conveys the least information (i.e. has maximum entropy), over the distributions of all continuous random variables having the same range w .

In some cases there may be classification errors. This can be reflected by (usually subjectively) increasing the variances to overlap exposure categories.

- (ii) Where data for individual miners is available.

If the exposures for individual miners is (accurately) known, the variance for one single exposure is estimated by calculating the simple s^2 using all the data. Accurate data are rarely if ever known however. When there is uncertainty in the exposure of an individual miner it may be modelled as

$$x_i = \mu_i + \epsilon_i \quad (4.8)$$

where x_i is the reported exposure for the i th miner, μ_i the true (average) exposure, and ϵ_i the error. Assuming μ_i and ϵ_i to be independent, we may write:

$$\text{Var}(x_i) = \text{Var}(\mu_i) + \text{Var}(\epsilon_i) \quad (4.9)$$

This leads to the observation that the observed variance is inflated by the presence of uncertainty in the reported value and that the true miner to miner variation is less than the apparent figure.

For purposes of regression and similar investigations, $\text{Var}(\epsilon_i)$ can be properly handled provided a treatment takes into account the total variance of x_i . Of course the result is less certain than if there were no error present.

4.3 Application of EVM Regression Model to Miner Groups

4.3.1 U.S. Miners

All White Miners

U.S. miner data with follow-up to 31 December 1982, are shown for all white miners, for uranium only miners, for miners with exposure prior to 1950, and for miners with no exposure prior to 1950 in Tables 4.1, 4.2, 4.3 and 4.4, respectively. The values given in Tables 4.1 to 4.4 were calculated directly from the raw data for the U.S. cohort.

The results of applying the EVM technique to the total group of white U.S. miners are shown in Figures 4.1 and 4.2 for the absolute risk model and the relative risk model, respectively.

Table 4.1

INCIDENCE OF LUNG CANCER FOR ALL WHITE U.S. MINERS

<u>Exposure Category (WLM)</u>	<u>Observed Lung Cancers</u>	<u>Expected Lung Cancers</u>	<u>Person Years</u>	<u>Average Exposure* (WLM)</u>	<u>Standard Deviation of Exposure*</u>	<u>Number of Miners*</u>
0- 119.9	10	10.7	17736	51.6	35.6	723
120- 359.9	33	11.2	18233	233.1	69.2	801
360- 839.9	54	12.5	17634	572.8	138.4	823
840-1799.9	60	9.3	12504	1230	271.0	594
1800-3719.9	70	5.2	6173	2515	490.1	324
3720+	32	1.4	1620	5777	2991	94
All Categories	259	50.4	73899	828.7	1228	3359

Notes:

- * Applies only to those miners whose total lifetime exposure is within indicated category.

Table 4.2

INCIDENCE OF LUNG CANCER FOR URANIUM ONLY U.S. MINERS

Exposure Category (WLM)	Observed Lung Cancers	Expected Lung Cancers	Person Years	Average Exposure* (WLM)	Standard Deviation of Exposure*	Number of Miners*
0- 119.9	3	4.78	10834	52.6	35.4	427
120- 359.9	11	5.23	10850	229.7	69.2	456
360- 839.9	17	5.43	9994	571.9	141.9	437
840-1799.9	29	4.61	7827	1224	267.4	355
1800-3719.9	45	3.26	4016	2532	498.3	200
3720+	20	0.73	884	5063	1283	51
All Categories	125	24.0	44405	818.4	1061	1926

Notes:

- * Applies only to those miners whose total lifetime exposure is within indicated category.

Table 4.3

**INCIDENCE OF LUNG CANCER FOR U.S. MINERS WITH EXPOSURES
PRIOR TO 1950**

<u>Exposure Category (WLM)</u>	<u>Observed Lung Cancers</u>	<u>Expected Lung Cancers</u>	<u>Person Exposure Years</u>	<u>Average* Exposure (WLM)</u>	<u>Standard Deviation of Exposure*</u>	<u>Number of Miners*</u>
0- 119.9	1	0.66	786	60.1	29.1	30
120- 359.9	3	1.04	1470	254.3	72.5	53
360- 839.9	6	2.41	2702	580.8	141.5	114
840-1799.9	19	3.64	3946	1290	289.6	178
1800-3719.9	46	3.34	3603	2564	489.0	188
3720+	16	0.97	1003	4988	1898	63
All Categories	91	12.1	13510	1769	1533	626

Notes:

- * Applies only to those miners whose total lifetime exposure is within indicated category.

Table 4.4

INCIDENCE OF LUNG CANCER FOR U.S. MINERS WITH NO EXPOSURES
PRIOR TO 1950

<u>Exposure Category (WLM)</u>	<u>Observed Lung Cancers</u>	<u>Expected Lung Cancers</u>	<u>Person Years</u>	<u>Average* Exposure (WLM)</u>	<u>Standard Deviation of Exposure*</u>	<u>Number of Miners*</u>
0- 119.9	9	10.1	16950	51.2	35.8	693
120- 359.9	30	10.1	16762	231.6	68.8	748
360- 839.9	48	10.1	14932	571.5	138.0	709
840-1799.9	41	5.7	8558	1204	258.7	416
1800-3719.9	24	1.9	2570	2446	485.0	136
3720+	16	0.47	616	7382	4040	31
All Categories	168	38.4	60389	613.4	1034	2733

Notes:

- * Applies only to those miners whose total lifetime exposure is within indicated category.

(Please note that unlike other Chapters, in view of the large number of Figures in this Chapter, Figures are located at the end of the Chapter to improve readability.) There is no apparent reason to reject the presumption of a linear exposure-effect relationship for either the absolute or relative risk model. Marginal probability distributions for the slopes of the absolute and the relative risk models are also provided in the "b" portions of Figure 4.1 and 4.2, respectively. Overall, the best estimate of risk for the group of white U.S. miners as a whole is about 3.78×10^{-6} cases per person-year per WLM and 0.46% per WLM for the absolute and relative models, respectively.

Uranium Only Miners

Figures 4.3 and 4.4 show the results of applying the EVM model to data for U.S. miners with uranium experience only for the absolute risk model and the relative risk model, respectively. In general terms, results of these regressions are similar to analyses for the U.S. miners as an overall group.

Miners With Pre-1950 Exposure

Figures 4.5 and 4.6 show the results of applying the EVM model to U.S. miners with (at least some) exposure prior to 1950 for the absolute and relative risk models, respectively.

When one moves from the whole U.S. miner cohort to the cohort with uranium only experience, the intercept in the relative risk model moves from positive to slightly negative, neither intercept being significantly different from zero.

To further illustrate the application of the EVM model, and to illustrate a peculiarity of the data for miners with pre-1950 exposure, the marginal probability distribution for the intercept

in the absolute risk model for U.S. miners with exposures prior to 1950 was calculated. This marginal probability distribution is shown in Figure 4.5c. The average intercept is -5×10^{-4} cases per PYR while the modal (most probable) value is -10.55×10^{-4} cases per PYR. As can be seen from the shaded area in Figure 4.5c, there is an 85% chance that the intercept is negative.

Miners With No Pre-1950 Exposure

Figures 4.7 and 4.8 show the results of applying the EVM regression model to U.S. uranium miner data for miners with no pre-1950 exposure. While all of the analyses of U.S. data show similar results, the EVM analysis of the relative risk model for this data set agrees most closely with a linear, no-threshold exposure-effect hypothesis.

4.3.2 Ontario Miners

No Gold Mining Experience

Data for Ontario uranium miners with no gold mining experience and with a cut-off date of 31 December 1981 are given in Table 4.5. The standard deviations of the exposures were calculated as the exposure interval divided by the square root of 12. As stated earlier (Section 4.2.2), this was based on the assumption of a uniform distribution of exposures within each exposure category. Data for the U.S. miners (i.e. Tables 4.1 to 4.4), for which individual miner exposures were available and for which the standard deviations could be calculated directly from the data, support this calculational method.

Figures 4.9 and 4.10 show the results obtained by applying the EVM technique to the data in Table 4.5 for the absolute risk

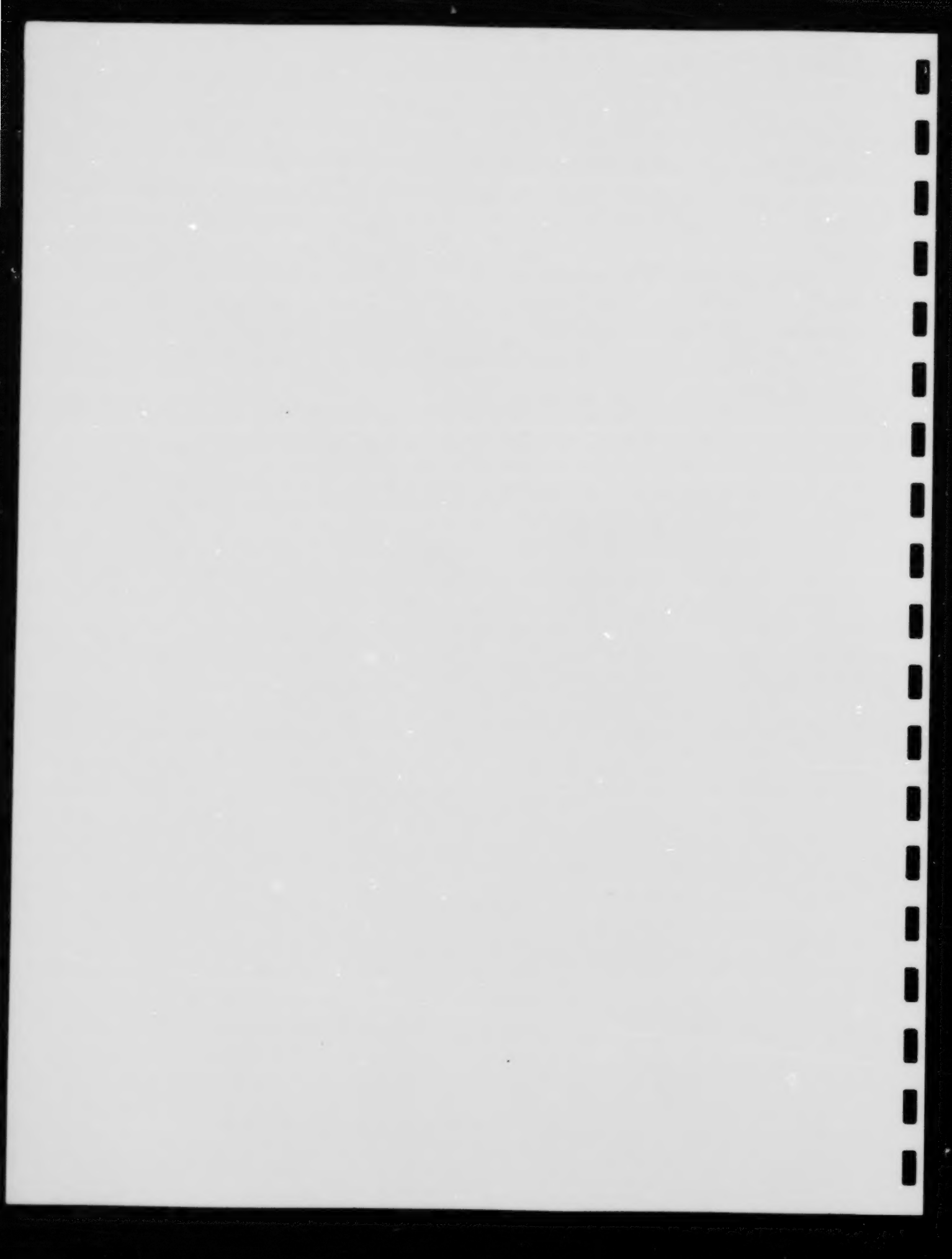
Table 4.5

ONTARIO URANIUM MINERS - NO GOLD MINING EXPERIENCE
(CUT-OFF 31 DECEMBER 1981)

<u>Exposure¹</u> <u>Category (WLM)</u>	<u>Observed</u> <u>Lung</u> <u>Cancers</u>	<u>Expected</u> <u>Lung</u> <u>Cancers</u>	<u>Person</u> <u>Years</u>	<u>Average</u> <u>Exposure</u> <u>(WLM)</u>	<u>Standard</u> <u>Deviation</u> <u>of</u> <u>Exposure³</u>	<u>Number</u> <u>of</u> <u>Miners²</u>
0.1 - 6	14	11.7	51,356	3	1.7	2,868
6.1 - 20	13	17.2	61,823	12	4.0	3,451
10.1 - 40	15	11.0	38,751	29	5.8	2,164
40.1 - 70	13	7.0	23,313	53	8.7	1,302
70.1 - 140	12	6.0	17,345	98	20.2	969
>140	<u>15</u> 82	<u>4.1</u> 57.0	<u>10,208</u> 202,796	200	50.0	<u>570</u> 11,324

Note:

- ¹ Data from Muller et al. (1984) using standard WLM.
- ² Based on a total of 15,984 uranium miners including mill workers (Muller et al., 1984) and divided between those with and without gold mining experience in proportion to person-years at risk in each exposure category.
- ³ Standard deviation calculated as exposure interval/square root of 12, except for last category which was subjectively chosen (see Section 4.2.2).



model and the relative risk model, respectively.

For both the absolute and relative risk models, the intercepts on the response axis are slightly, although not significantly, negative. The best estimate of the absolute risk coefficient is 4.43×10^{-6} cases per person-year per WLM. The best estimate of the relative risk coefficient is 1.28% per WLM. While there is some scatter about the regression line, the scatter is well within normal statistical variation as illustrated by the marginal probability distributions for response for some selected data points, as shown on Figures 4.9a and 4.9b.

Miners With Gold Mining Experience

Data for Ontario uranium miners with gold mining experience and a cut-off date of 31 December 1981 are shown in Table 4.6.

Figures 4.11 and 4.12 show the results of applying the EVM technique to the data in Table 4.6 for the absolute risk model and the relative risk models, respectively.

The intercepts at zero WLM exposure are significantly different than the intercepts calculated for Ontario miners with no prior gold mining experience. This aspect is discussed below. It is also of interest to note that, in the case of the absolute risk model, the risk coefficient calculated for the Ontario Miners with prior gold mining experience is nearly twice as large as that calculated for the Ontario miners without prior gold mining experience. Conversely, the relative risk coefficient calculated for Ontario miners with gold mining experience is only about 60% of that calculated for Ontario miners without prior gold mining experience. In both cases, the 97.5% probability range for the risk coefficients, either absolute or relative, is larger (i.e. we are less certain about the risk coefficients) for the miners

with previous gold mining experience than for the miners without prior gold mining experience. These observations reflect the increased uncertainty introduced in the analyses via the inclusion of uranium miners with prior and undefined exposures to lung carcinogens (possibly including radon) associated with previous gold mining experience.

Finally, it may be worth noting that the marginal (posterior) probability density functions for both the absolute and relative risk coefficients include zero (i.e. no excess) as possible (although unlikely) values.

Intercepts

Figures 4.13 and 4.14 show the marginal (posterior) probability distributions for the intercepts for the two Ontario miner cohorts of uranium miners, those with and without gold mining experience, for the absolute risk model and the relative risk models, respectively.

Parts a) of these figures show marginal probability distributions for the intercepts for each cohort separately, whereas parts b) of these figures show the marginal probability distributions for the difference between the intercepts for miners with and without gold experience.

It is clear from an examination of either Figure 4.13b for the absolute risk model or Figure 4.14b for the relative risk model that the difference between the intercepts for the absolute risk model is real and statistically significant at the 2% level. The difference for relative risk models is statistically significant at the 1% level. This finding is consistent with observations made by Muller et al. (1984). Intuitively, the data suggest a pre-existing risk for those miners with previous gold mining

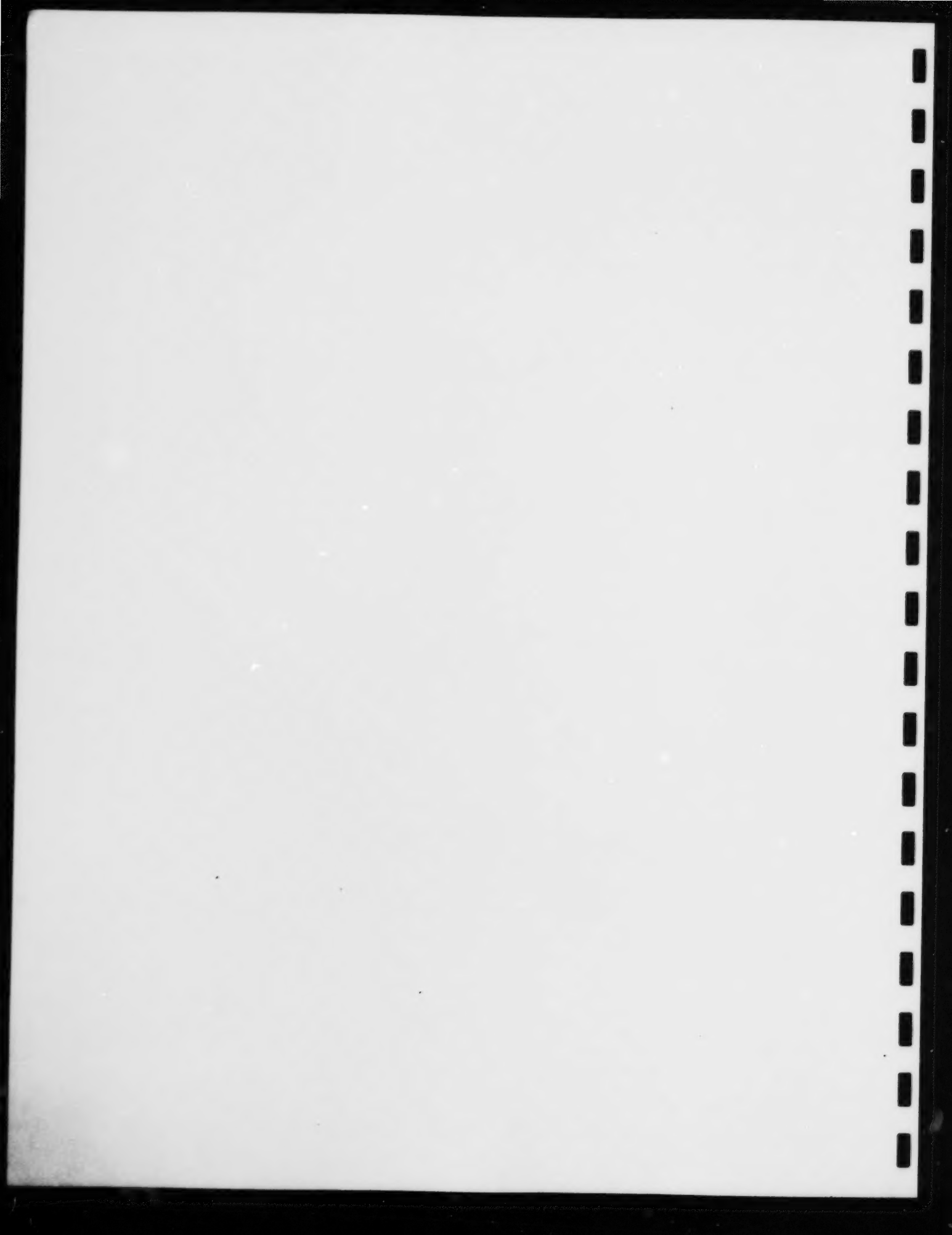
Table 4.6

ONTARIO URANIUM MINERS - WITH GOLD MINING EXPERIENCE
(CUT-OFF 31 DECEMBER, 1981)

<u>Exposure Category (WLM)</u>	<u>Observed Lung Cancers</u>	<u>Expected Lung Cancers</u>	<u>Person Years</u>	<u>Average Exposure (WLM)</u>	<u>Standard Deviation of Exposure³</u>	<u>Number of Miners²</u>
0.1 - 6	14	8.8	20,354	3	1.7	1,136
6.1 - 20	23	12.4	24,190	12	4.0	1,351
10.1 - 40	17	8.5	15,668	29	5.8	875
40.1 - 70	11	7.0	10,524	53	8.7	588
70.1 - 140	16	5.9	8,629	98	20.2	482
>140	<u>11</u>	<u>3.4</u>	<u>4,094</u>	200	50.0	<u>228</u>
	92	46.0	83,459			4,660

Note:

- 1 Data from Muller et al. (1984) using standard WLM.
- 2 Based on a total of 15,984 uranium miners including mill workers (Muller et al., 1984) and divided between those with and without gold mining experience in proportion to person-years at risk in each exposure category.
- 3 Standard deviation calculated as exposure interval/square root of 12 except for last category which was subjectively chosen (see Section 4.2.2).



experience. This suggests that, where feasible, uranium mining cohorts with other hard rock mining experience should be analysed separately from cohorts without other hard rock mining experience. This applies irrespective of our knowledge of radon daughter levels in these mines because lung carcinogens other than radon or modifying agents may be present in mine air.

4.3.3 Czechoslovakian Miners

The data used for examination of the Czechoslovakian mines are shown in Table 4.7. The group A shown here has a relatively early cutoff date. The reason for this is that, while later follow-ups are reported in the literature, the data for the later follow-ups are not as complete as that given in Table 4.7, especially with regard to the numbers of miners in each exposure category. The results of applying the EVM technique to these data are shown in Figures 4.15 and 4.16 for the absolute and relative risk models, respectively.

For both the absolute and relative risk models, the EVM technique calculates a slightly negative, although not statistically significant, intercept, indicating that the Czech data are not inconsistent with a linear, no-threshold exposure-effect relation. For the absolute risk model, a risk coefficient of 13×10^{-6} cases per million person-years WLM is calculated. For the relative risk model, a risk coefficient of 1.5% per WLM is calculated.

Sevc et al. (1988) present data for a study group S, which includes the group A miners. Table 4 of this paper reports information on study group A which we believe may be comparable to the data in Figures 4.15 and 4.16. Sevc et al. (1988) present an absolute risk coefficient of 20 cases per million person-years per WLM and a relative risk coefficient of 1.5% per WLM. While

our estimate of the absolute risk coefficient is somewhat less at 13 cases per million person-years per WLM, our estimate of the relative risk coefficient is identical (albeit perhaps fortuitous) at 1.5% per WLM. Since the calculations are sensitive to the numbers of cases, smoking experience and other factors in addition to radon daughter exposure, this agreement is very good. Moreover, on the presumption that whatever vagaries exist in the miner group also exist in the control group, the relative risk coefficient may be somewhat less sensitive to uncertainties in these factors.

4.3.4 Eldorado Beaverlodge Miners

Data used in the analysis of the Eldorado Beaverlodge miners are shown on Table 4.8. It is noteworthy that approximately 50% of the total person-years of experience in this cohort is in the lowest (0-4 WLM) exposure category. The results from applying the EVM technique to these data are shown on Figures 4.17 and 4.18 for the absolute and the relative risk models, respectively.

Again, the linear, no-threshold model seems appropriate. However, examination of Figures 4.17 and 4.18 suggest some scatter about the regression line; for the highest exposure category, the EVM technique may underpredict the risk. In this regard, it is worth noting that in all exposure categories above 24 WLM, the numbers of observed cases are very small and subject to considerable statistical uncertainty, as are the WLM estimates themselves.

4.3.5 Port Radium Miner Study

The data used in the EVM analyses of Port Radium miners are given in Table 4.9. The results of applying the EVM technique to these data are shown on Figure 4.19 and 4.20 for the absolute and

Table 4.7

CZECHOSLOVAKIAN EPIDEMIOLOGICAL DATA - GROUP A MINERS (1)
(CUT-OFF DATE 31 DECEMBER, 1973)

Exposure ¹ Category (WLM)	Observed Lung Cancers	Expected Lung Cancers	Person Years	Average Exposure (WLM) ²	Standard Deviation of Exposure ³	Number of Miners
<100	6	5.16	9,380	74	28.9	186
100 - 199	40	12.26	16,131	150	28.9	657
200 - 399	84	15.10	19,614	290	57.7	940
>400	<u>82</u>	<u>9.94</u>	<u>11,830</u>	570	100	<u>650</u>
	212	42.46	56,955			2,433

Notes:

- 1 From Kunz and Sevc (1978) (Table 1 (American method) and prorated for number of person-years) except for number of miners taken from Sevc et al. (1971).
- 2 Note that Kunz et al. (1979) gives slightly different average exposures i.e. 72, 150, 285, and 570 WLM; however, Kunz et al. (1979) does not give person-years of exposure and so is not used here.
- 3 Standard deviation calculated as exposure interval/square root of 12 except for last category which was subjectively chosen (see Section 4.2.2).

Table 4.8

ELDORADO BEAVER LODGE

Exposure Category (WLM)	Observed Lung Cancers	Expected ¹ Lung Cancers	Person Years	Average Exposure ¹ (WLM)	Standard Deviation of Exposure ²	Number ³ of Miners
0 - 4	14	14.46	29,818	0.9	2	4444
5 - 24	12	6.48	14,815	11.7	5	2208
25 - 49	5	2.64	5,554	35.6	7	828
50 - 99	6	2.48	3,755	69.8	14	560
100 - 149	7	1.17	1,607	121.1	14	240
150 - 249	6	0.76	1,051	187.4	29	157
≥ 250	<u>4</u>	<u>0.28</u>	<u>342</u>	<u>294.9</u>	45	<u>50</u>
Total	54	28.27	56,942	20.2		8487

Note:

- 1 Howe et al. (1986, Table 3) with first 10 years of follow-up excluded.
- 2 Range/square root of 12, except for 0-4 category taken as 2, and ≥ 250 category/taken as 45 (see Section 4.2.2).
- 3 Prorated on basis of PYR for 8487 men in cohort, some 4077 were never employed underground.

Table 4.9

PORT RADIUM MINERS¹

Exposure ¹ Category (WLM)	Observed Lung Cancers	Expected Lung Cancers	Person Years	Average Exposure (WLM)	Standard ² Deviation of Exposure	Number ³ of Miners
0-4	14	10.99	14,494	0.41	2	879
5-99	6	4.29	9,993	37.05	27	606
100-199	5	1.79	3,149	142.78	29	191
200-399	6	1.66	3,023	281.49	57	183
400-799	4	1.42	1,804	588.75	115	109
800-1599	5	1.65	1,281	1088.05	230	78
≥ 1600	<u>8</u>	<u>1.05</u>	<u>929</u>	<u>2392.67</u>	600	<u>57</u>
TOTAL	48	22.85	34,673	183.30		2,103

Notes:

- ¹ Cohort consists of 2103 (2696 initial - 593 due to loss to follow-up).
- ² Standard deviation calculated as exposure interval/square root of 12 except for the first and last categories which were subjectively chosen (see Section 4.2.2).
- ³ Estimated, based on person-years of exposure.



relative risk models, respectively.

Again, the EVM results are not inconsistent with a linear, no-threshold exposure-effect model. In this instance, the intercepts are slightly positive at zero WLM exposure although not significantly so. The uncertainties associated with this group of miners are large, in part due to the small numbers of cases. Part of the scatter may be due to uncertainties introduced via incomplete work histories as well.

4.3.6 Newfoundland Fluorspar Miners

The data used in the EVM analyses of the Newfoundland fluorspar miners are shown on Table 4.10. While the number of cases observed is large, the group itself is small and compared to several other groups has a relatively small number of person-years of experience, just under 30,000 person-years with exposures assigned.

The results of applying the EVM technique to the data in Table 4.10 are shown in Figures 4.21 and 4.22 for the absolute and relative risk models, respectively. Once again, the EVM regressions indicate that the data are not inconsistent with a linear, no-threshold model of exposure and response. As for the Beaverlodge and Port Radium studies, there is some scatter about the regression lines, which may in part be due to residual uncertainties about exposure estimation.

4.3.7 Swedish Iron Miners

The data used in the EVM analysis of the Swedish iron miners are shown on Table 4.11. The results of applying the EVM technique to these data are shown on Figures 4.23 and 4.24 for the absolute and the relative risk models, respectively.

Again, as for several of the previous analyses, the numbers of observed cases and the number of person-years are fairly small. In addition, for reasons noted previously, there are likely to be considerable uncertainties associated with the miners' exposures. The EVM analyses show significant scatter above the regression line. This is most noticeable in the exposure category between 100-149 cumulative WLM where the observed value is significantly lower than the regression line for either the absolute or relative risk model. In either case, the marginal probability distributions for excess risk are very large, which presumably reflects the small numbers and WLM uncertainties.

4.3.8 Summary of EVM Analyses

The results of the EVM analyses for the various study groups are summarized in Table 4.12 for both the absolute and relative risk models. The data summarized in this table include the calculated slopes, intercepts and the 95% probability range (i.e. from 2.5 to 97.5% probability) for both the absolute and relative risk models derived by the EVM method.

With a possible exception of the Swedish and Beaverlodge data, none of the data are inconsistent with a linear, no-threshold exposure effect relationship. In our view, the uncertainties associated with exposure estimation of the Beaverlodge and Swedish data, combined with small numbers in the Swedish study, are the most likely explanation for the relatively large scatter of the EVM regression lines in these two studies.

Table 4.10

NEWFOUNDLAND FLUORSPAR MINERS

Exposure Category (WLM)	Observed Lung Cancers ¹	Expected Lung Cancers ¹	Person Years ¹	Average Exposure ¹ (WLM)	Standard ² Deviation of Exposure	Number of Miners ³
>0 - 100	16	8.04	13,715.0	21.8	28.9	631
100 - 400	12	5.53	6,979.5	229.4	86.7	321
400 - 1000	14	3.25	4,281.0	607.3	173.2	197
1000 - 1600	14	1.20	1,733.5	1284.2	173.2	80
1600 - 2500	25	1.04	1,579.0	1964.8	259.81	73
> 2500	<u>29</u>	<u>0.79</u>	<u>1,169.5</u>	3449.1	548	<u>54</u>
TOTAL	110	19.9	29,457.50			1356

Notes:

- 1 Basic source of data Morrison et al (1988), Internal Controls.
- 2 Standard deviation = range/square root of 12, except for >2500 WLM category which was chosen subjectively (see Section 4.2.2).
- 3 1772 miners, prorated by exposure category on basis of FYR. Note that the study actually contains a total of 38,508.5 FYR. However, 9051 FYR have no exposure assigned to them and are excluded from calculation.

Table 4.11

SWEDISH IRON MINERS

Exposure (1) Category (WLM)	Observed ¹ Cases	Expected ¹ Cases	Person Years at Risk ¹	Mean Exposure ¹ (WLM)	Standard Deviation of Exposure ²	Number ³ of Miners
0 - 49	8	3.4	8,981	26.8	14	483
50 - 99	14	3.6	7,025	73.0	14	377
100 - 149	4	2.5	4,483	123.0	14	241
150 - 199	18	2.4	2,805	171.9	14	151
≥ 200	<u>6</u>	<u>1.0</u>	<u>789</u>	<u>217.7</u>	<u>30</u>	<u>42</u>
TOTAL	50	12.8	24,083	81.4		1294

Notes:

- 1 From Table 4, Radford and St. Clair Renard (1984).
- 2 Range/square root of 12 except for ≥ 200 taken as 30 WLM (see Section 4.2.2).
- 3 Prorated on basis of FYR for the 1294 miners alive as of January 1, 1951.

Table 4.12

SUMMARY OF RISK COEFFICIENTS DERIVED BY EVM METHOD

Miner Group	Absolute Risk Model		Relative Risk Model	
	Intercept ¹	Slope ²	Intercept ³	Slope ⁴
U.S. (all)	-6.7	3.8 [3.1, 4.5]	19	0.46 [0.37, 0.55]
U.S. (U only)	-4.1	3.5 [2.8, 4.3]	-61	0.50 [0.39, 0.62]
U.S. (pre 1950)	-5.0	3.9 [2.8, 4.9]	-51	0.41 [0.29, 0.53]
U.S. (no pre 1950)	-0.6	3.8 [2.9, 4.7]	-7.9	0.52 [0.39, 0.67]
Ontario (no gold)	-0.5	4.4 [2.0, 7.1]	-16	1.3 [0.6, 2.1]
Ontario (with gold)	2.5	7.1 [1.4, 14]	57	0.8 [0.0, 1.7]
Czech	-6.2	13 [9.7, 16]	-35	1.5 [1.0, 1.9]
Beaverlodge	-0.34	20 [9.9, 31]	-1.2	2.9 [1.4, 4.7]
Port Radium	1.3	2.5 [1.0, 4.3]	31	0.22 [0.07, 0.40]
Newfoundland	2.3	5.8 [4.4, 7.3]	29	0.83 [0.63, 1.0]
Swedish	-0.53	18 [7.5, 29]	69	2.0 [0.27, 3.7]

Notes:

- ¹ Cases per 10⁴ person-years.
- ² Cases per 10⁶ person-years per WLM: mean (2.5 percentile, 97.5 percentile).
- ³ Excess relative risk: mean (2.5 percentile, 97.5 percentile).
- ⁴ Excess relative risk per WLM: mean (2.5 percentile, 97.5 percentile).

FIGURE 4.1a
INCIDENCE OF LUNG CANCER FOR ALL WHITE U.S. MINERS
ABSOLUTE RISK MODEL
(SEE TABLE 4.1)

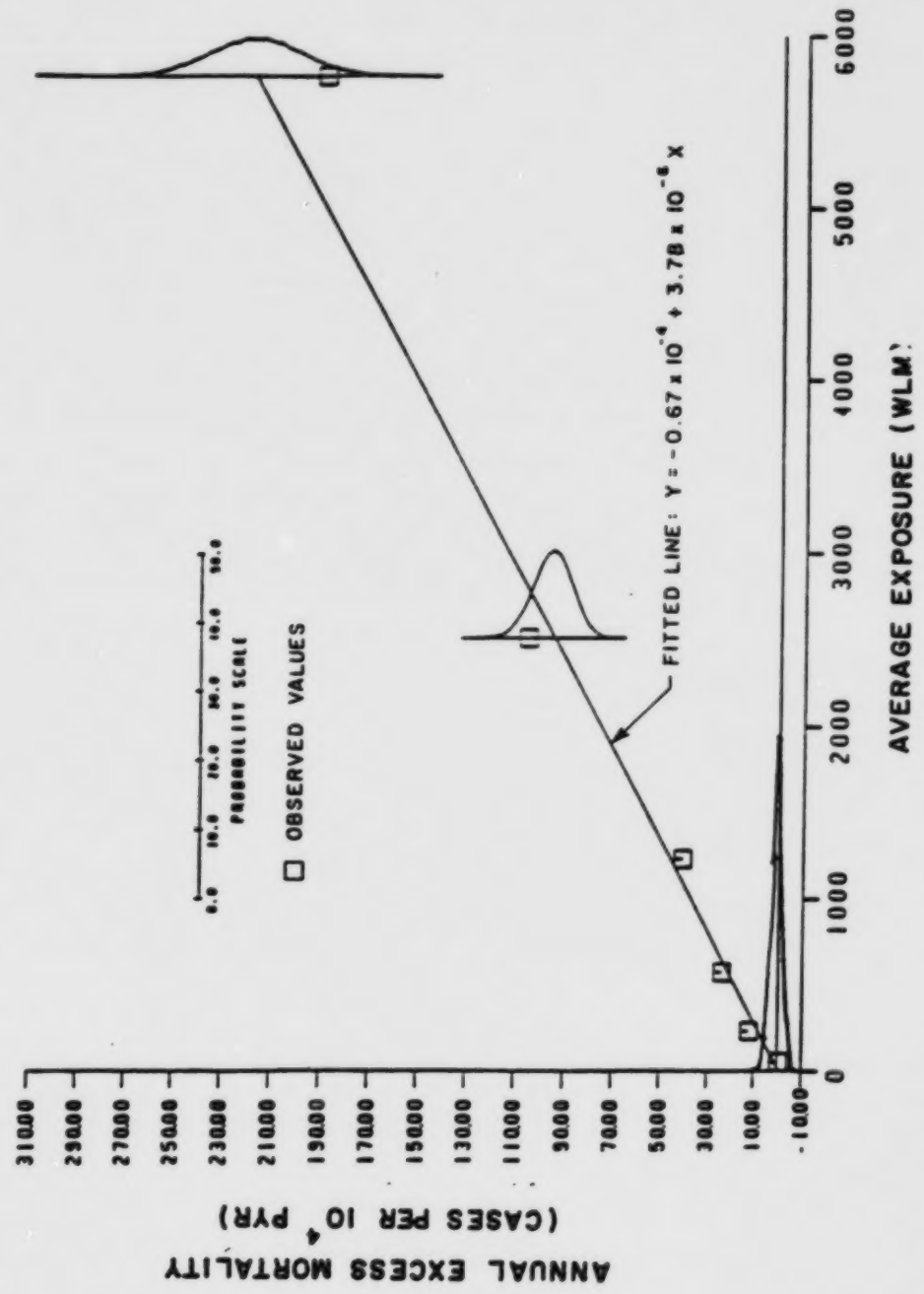


FIGURE 4.1b
MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)
ABSOLUTE RISK MODEL; ALL WHITE U.S. MINERS
(SEE TABLE 4.1)

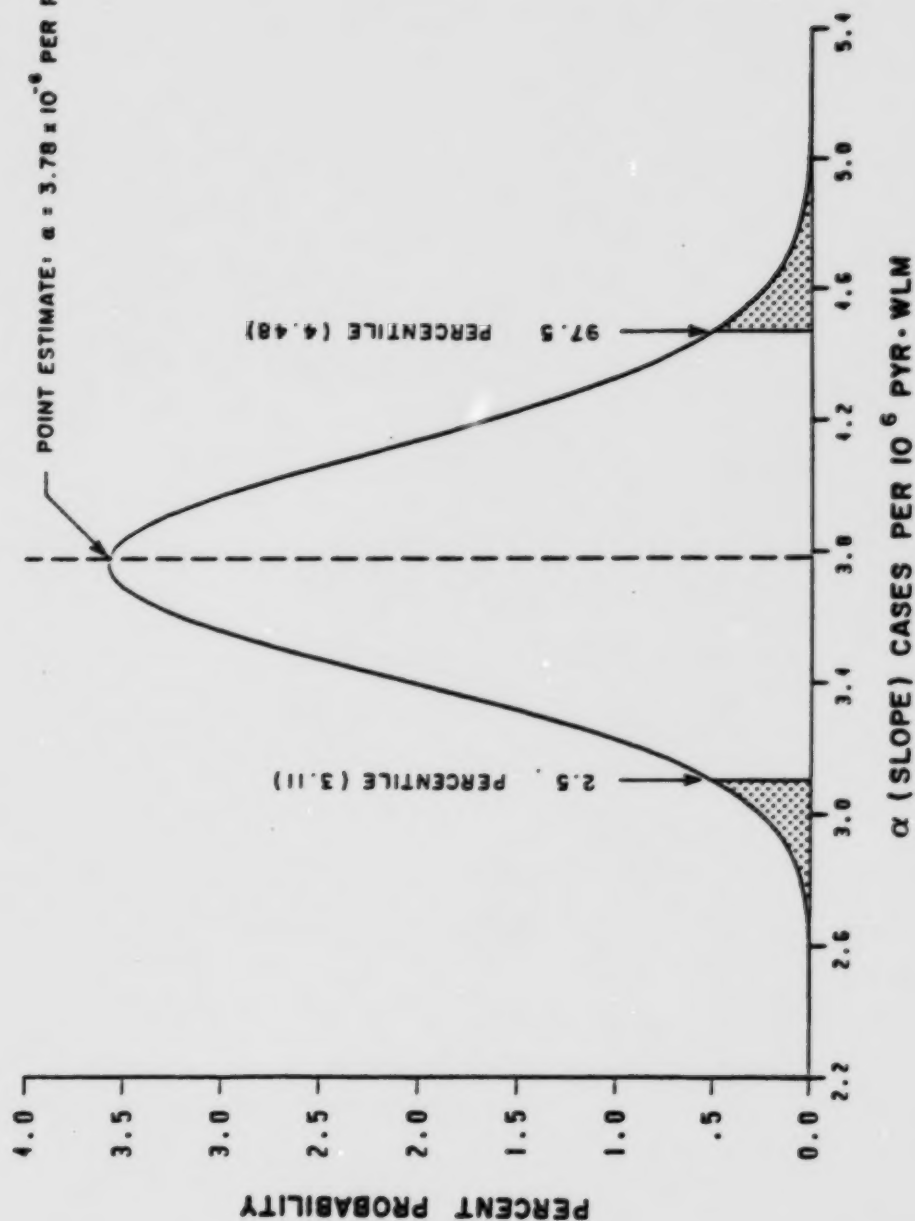


FIGURE 4.2a
INCIDENCE OF LUNG CANCER FOR ALL WHITE U.S. MINERS
RELATIVE RISK MODEL
(SEE TABLE 4.1)

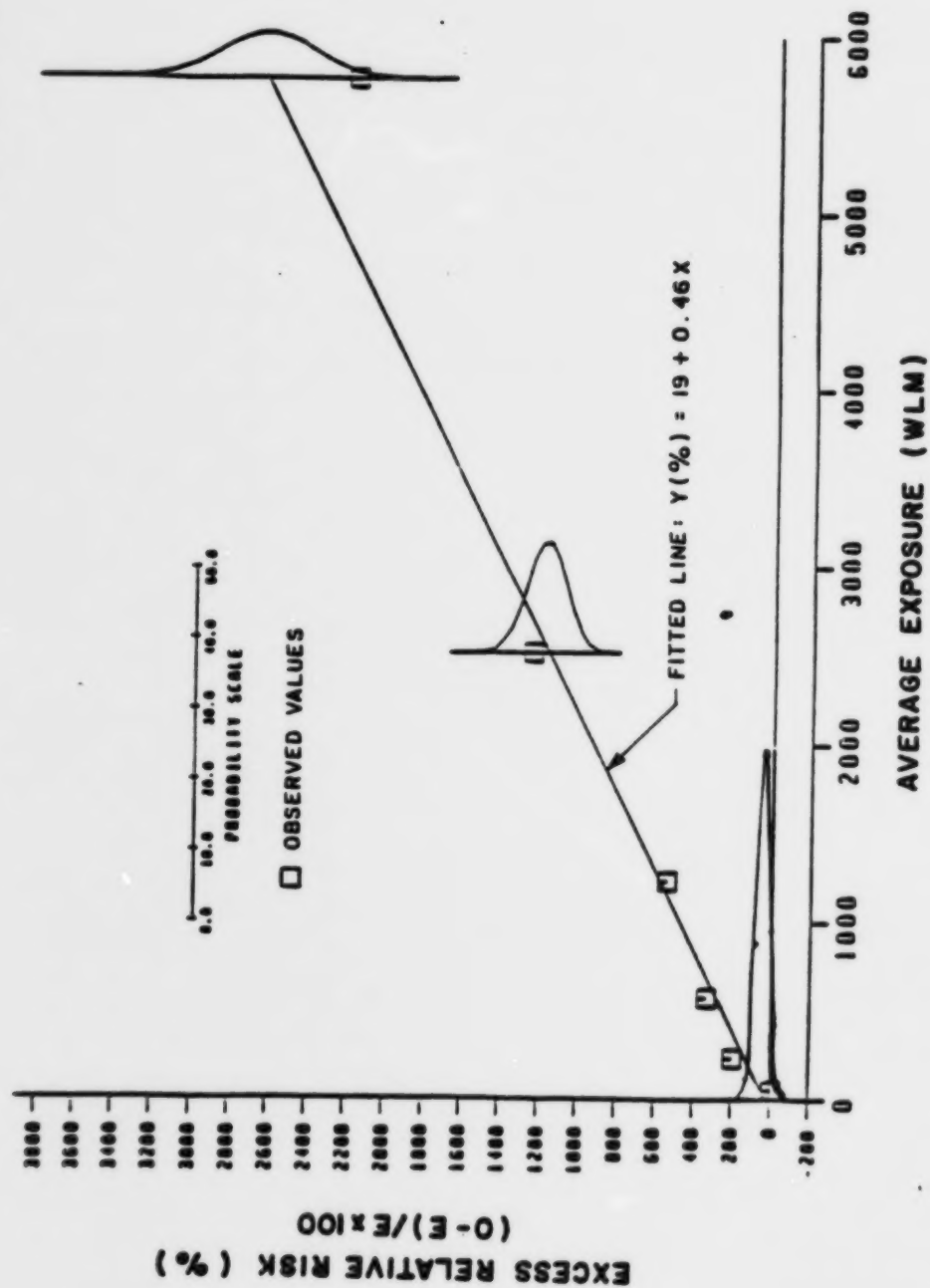


FIGURE 4.2b
MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)
RELATIVE RISK MODEL, ALL WHITE U.S. MINERS
(SEE TABLE 4.1)

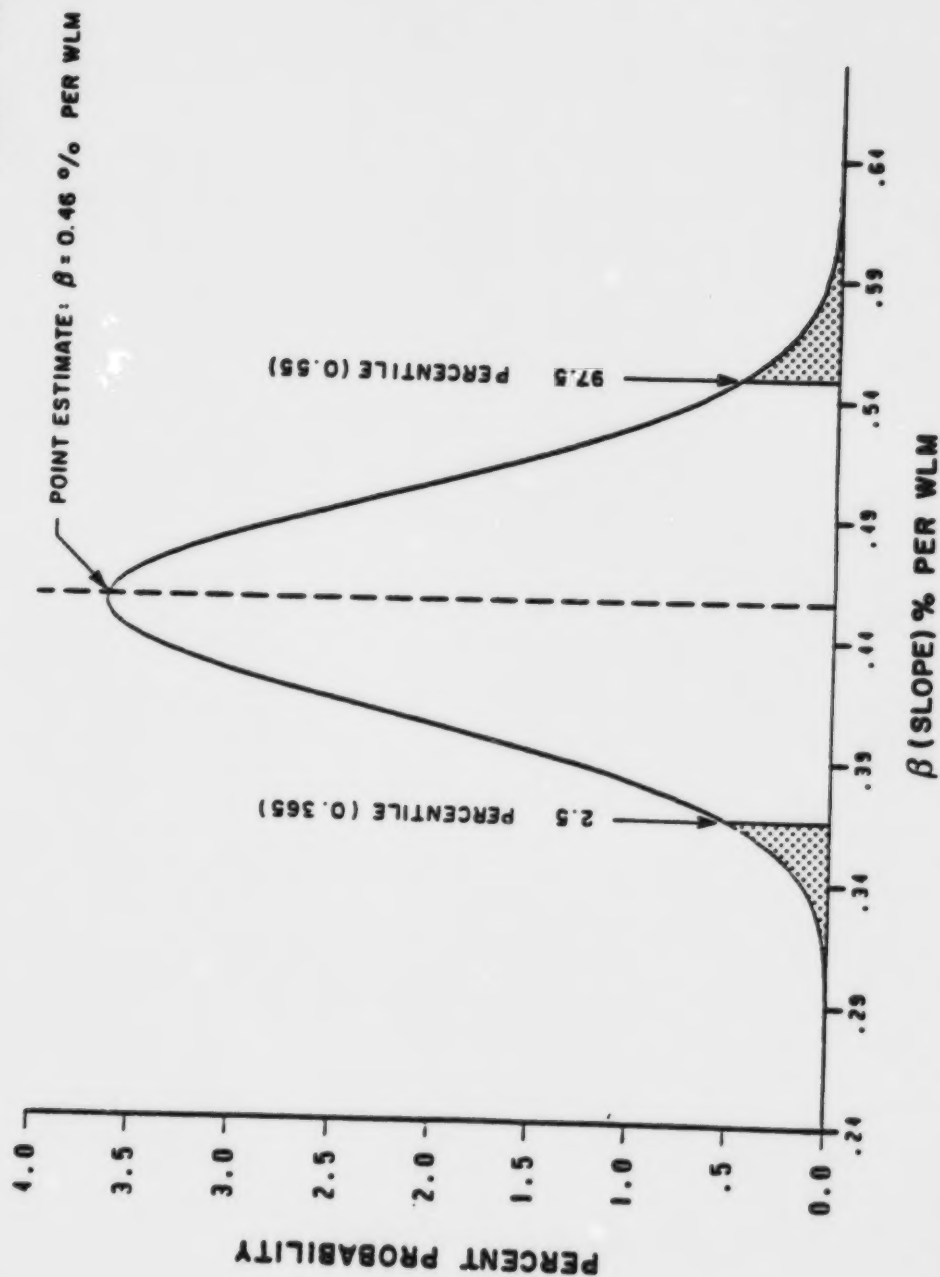


FIGURE 4.3a
INCIDENCE OF LUNG CANCER FOR U.S. URANIUM MINERS ONLY
ABSOLUTE RISK MODEL
(SEE TABLE 4.2)

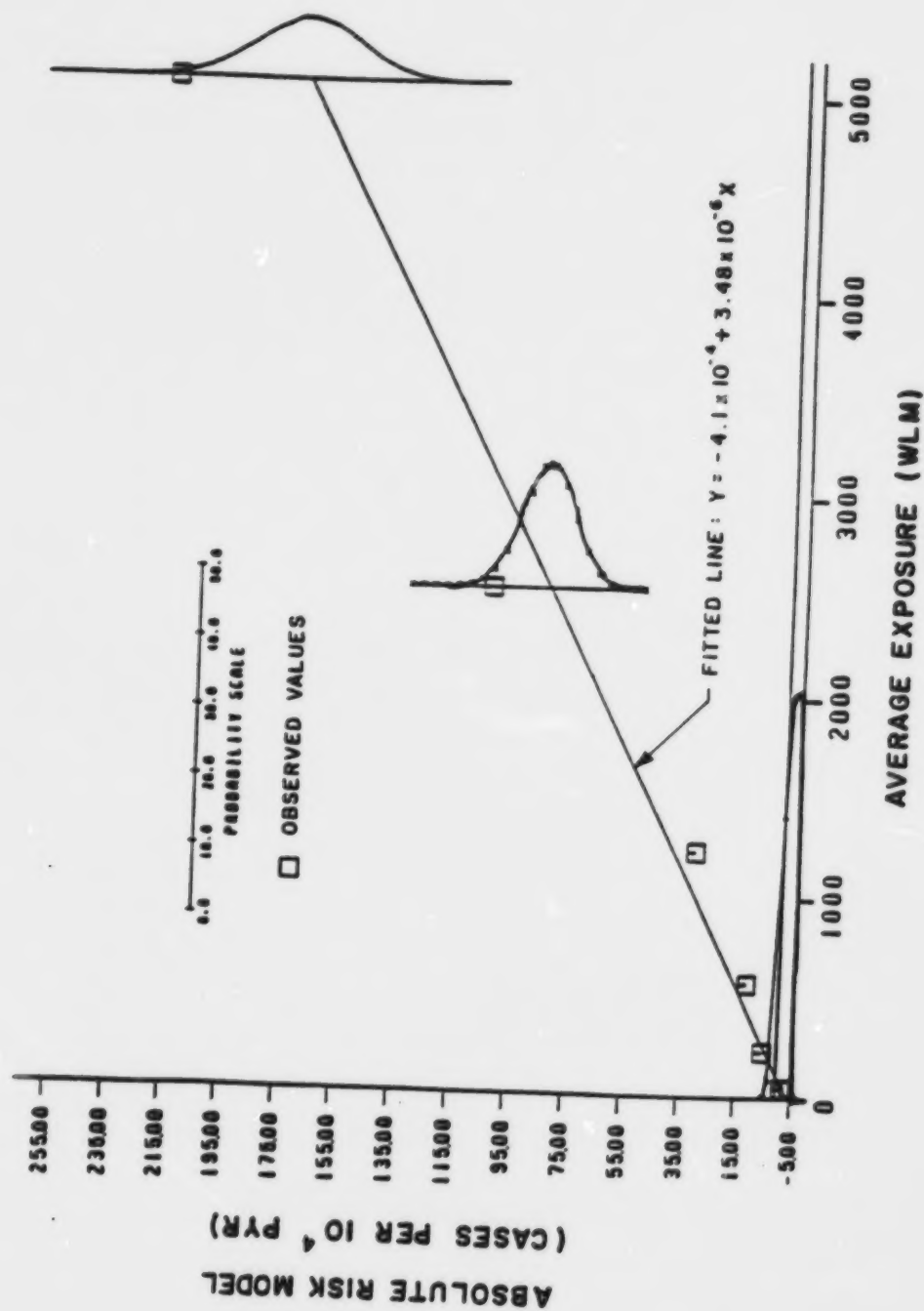


FIGURE 4.3b
MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)
ABSOLUTE RISK MODEL, U.S. URANIUM MINERS ONLY
(SEE TABLE 4.2)

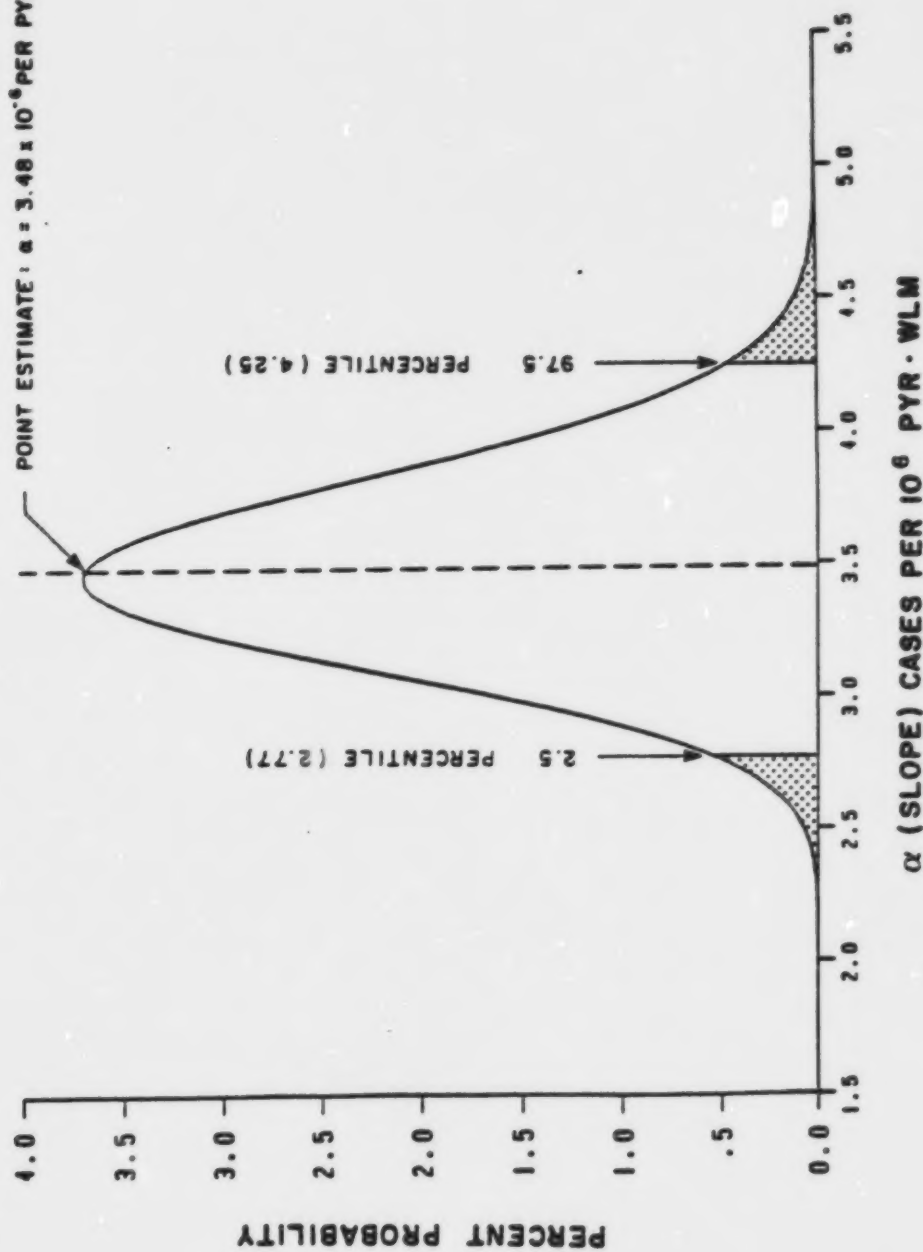


FIGURE 4.4a
INCIDENCE OF LUNG CANCER FOR U.S. URANIUM MINERS ONLY
RELATIVE RISK MODEL
(SEE TABLE 4.2)

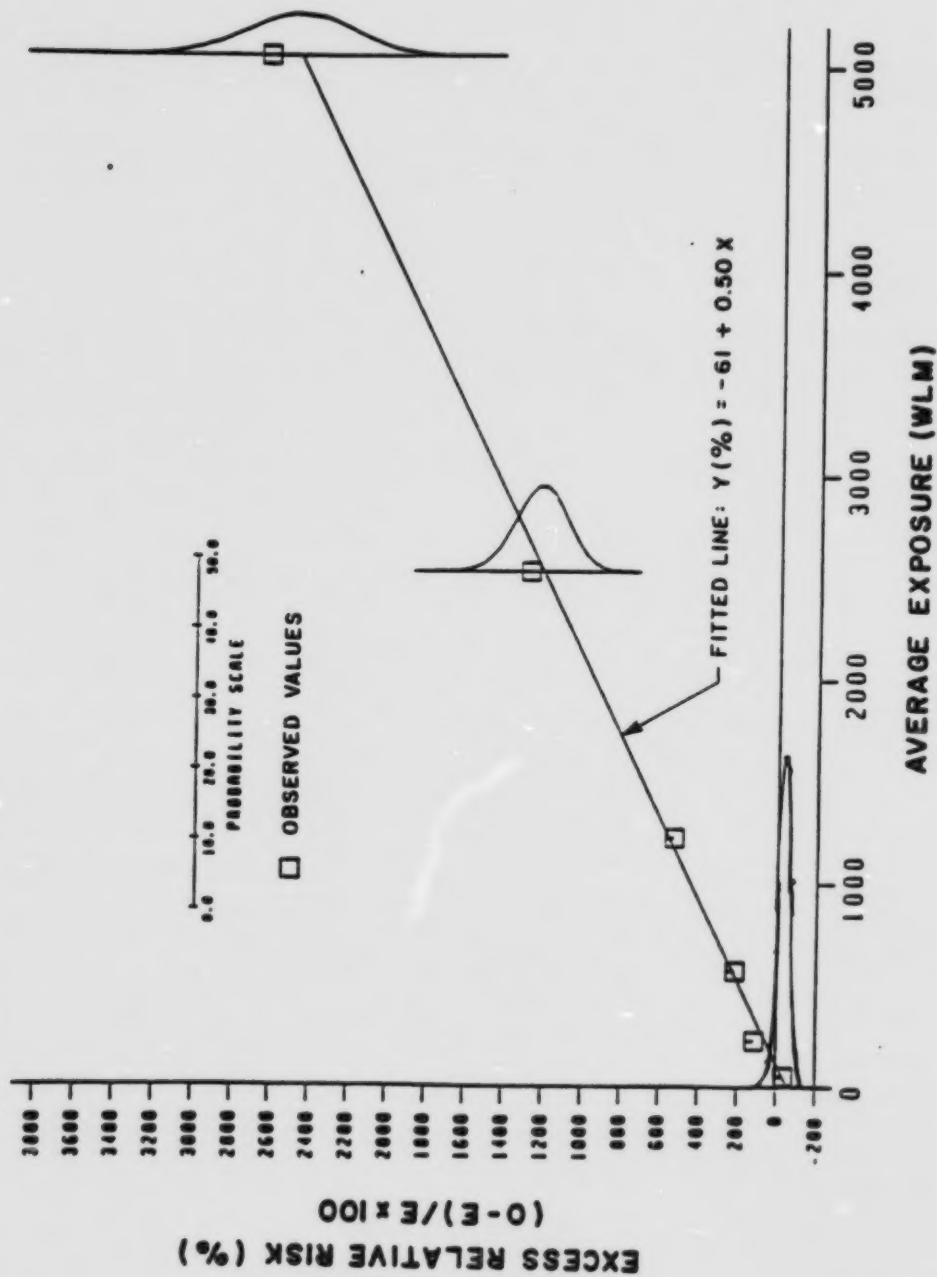


FIGURE 4.4b

MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)

RELATIVE RISK MODEL, U.S. URANIUM MINERS ONLY

(SEE TABLE 4.2)

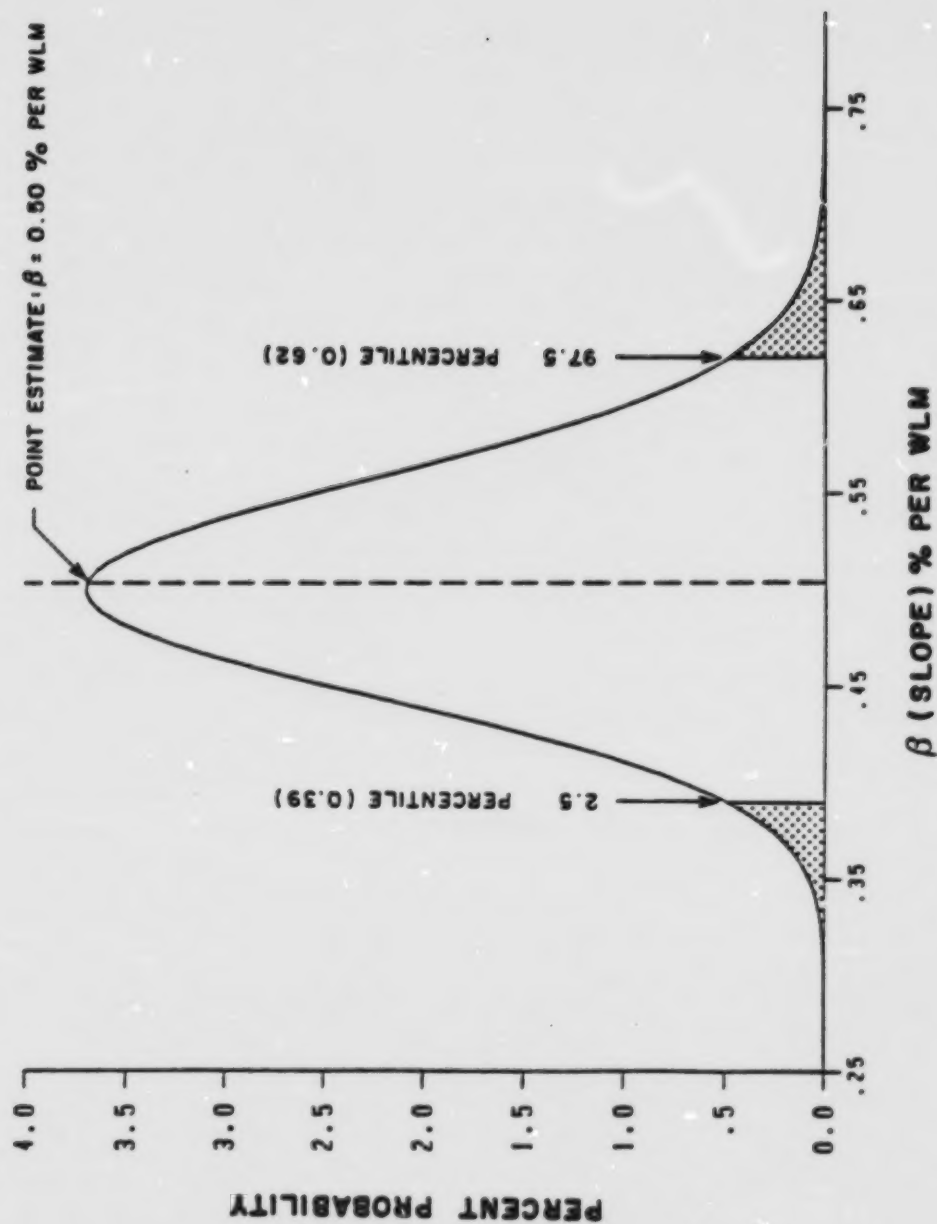


FIGURE 4.5a
INCIDENCE OF LUNG CANCER FOR U.S. MINERS WITH EXPOSURES PRIOR TO 1950
ABSOLUTE RISK MODEL
(SEE TABLE 4.3)

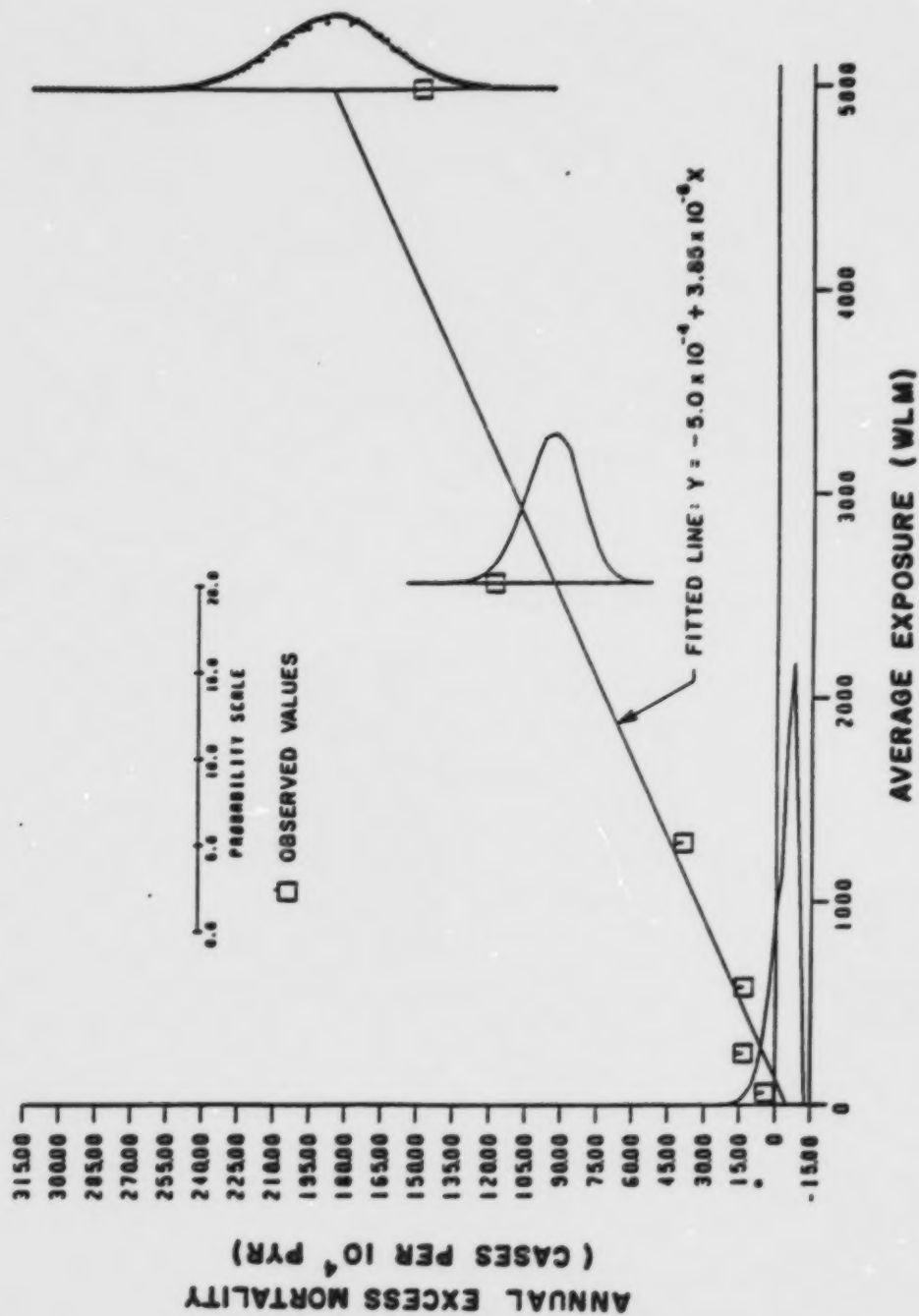


FIGURE 4.5b

MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)

ABSOLUTE RISK MODEL, U.S. MINERS WITH EXPOSURES PRIOR TO 1950

(SEE TABLE 4.3)

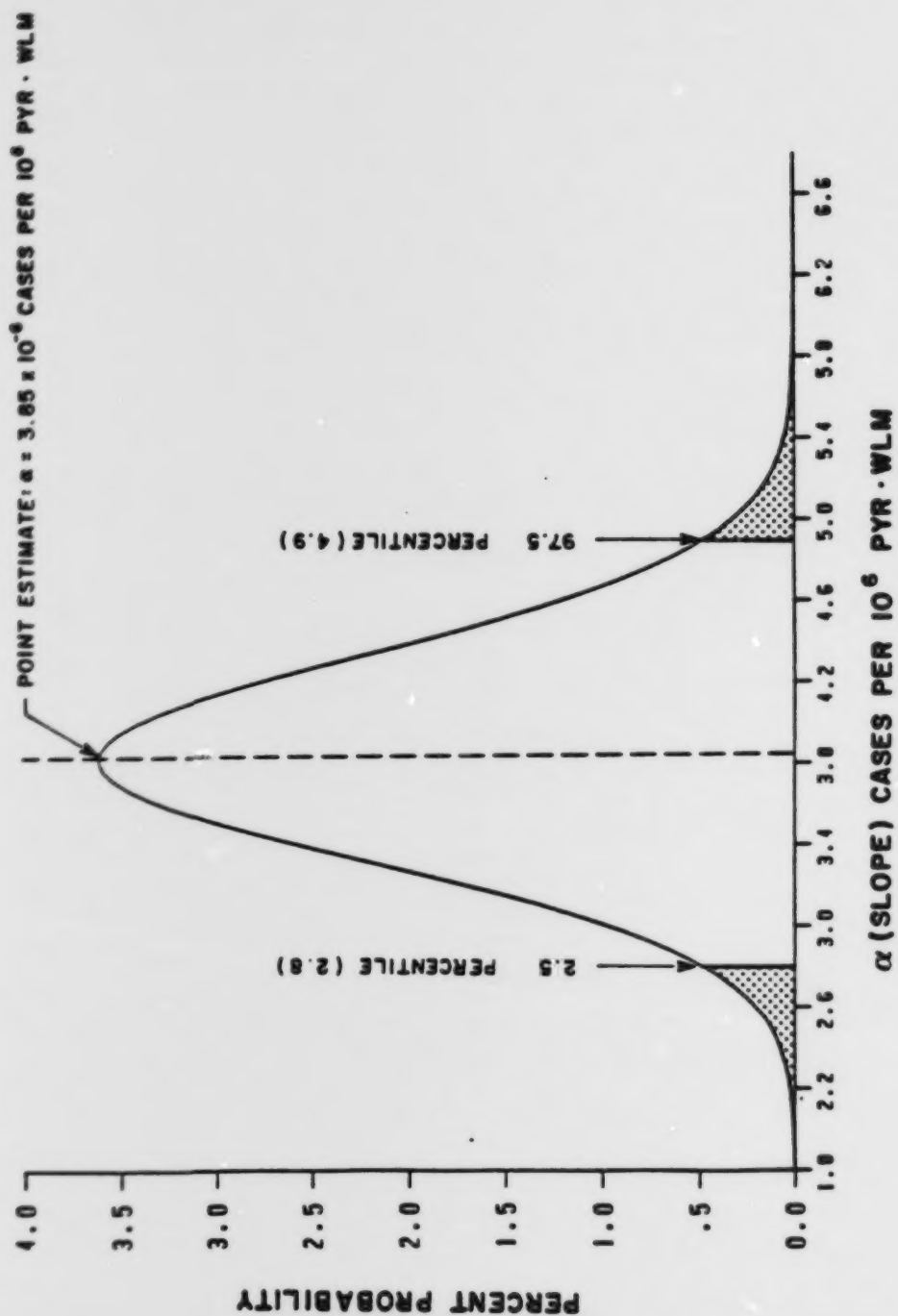


FIGURE 4.5c

MARGINAL PROBABILITY DISTRIBUTION
OF INTERCEPT (α_0)
FOR U.S. MINERS WITH EXPOSURES
PRIOR TO 1950
ABSOLUTE RISK MODEL
(SEE TABLE 4.3)

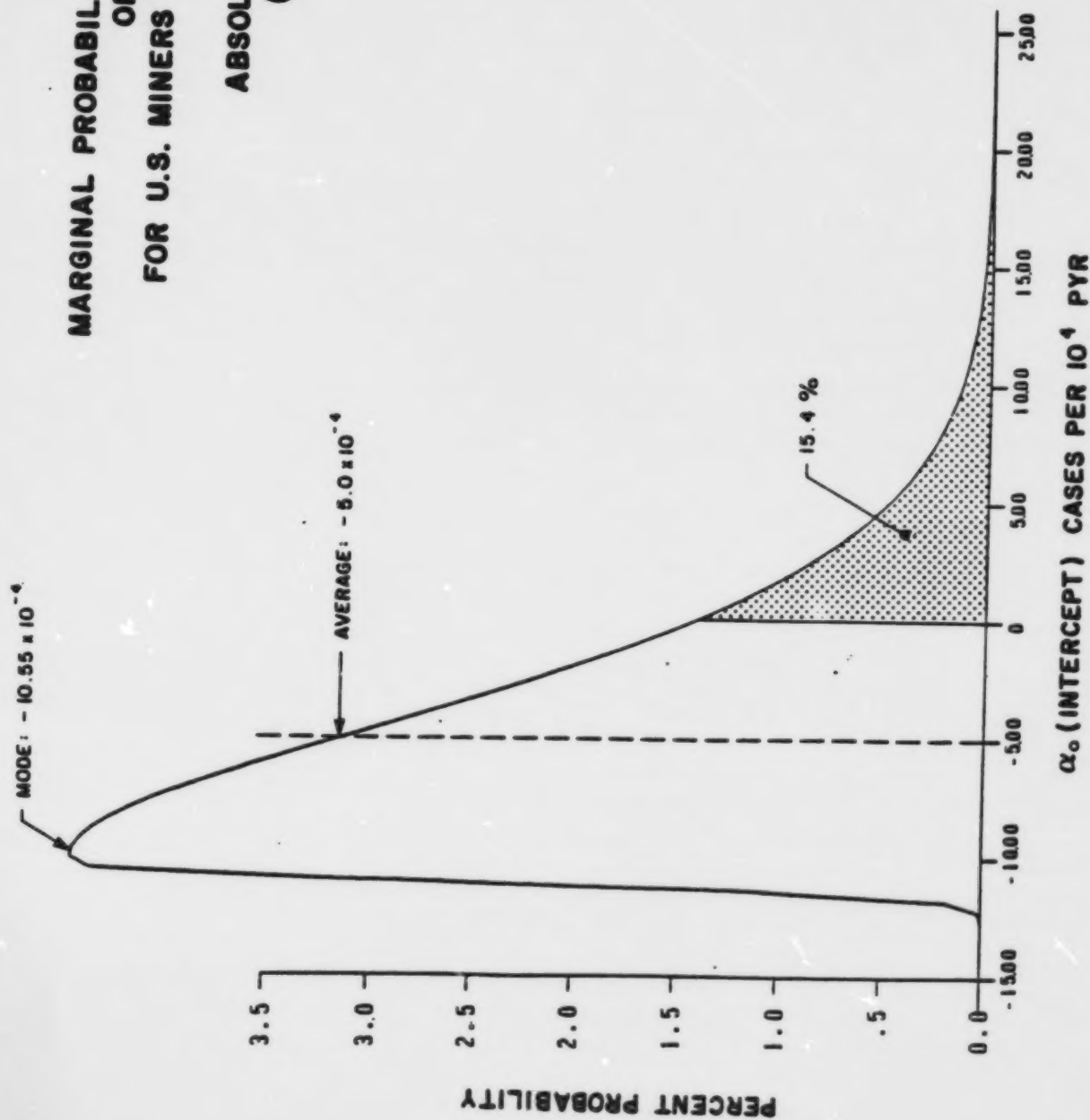


FIGURE 4.6a
INCIDENCE OF LUNG CANCER FOR U.S. MINERS WITH EXPOSURES PRIOR TO 1950
RELATIVE RISK MODEL
(SEE TABLE 4.3)

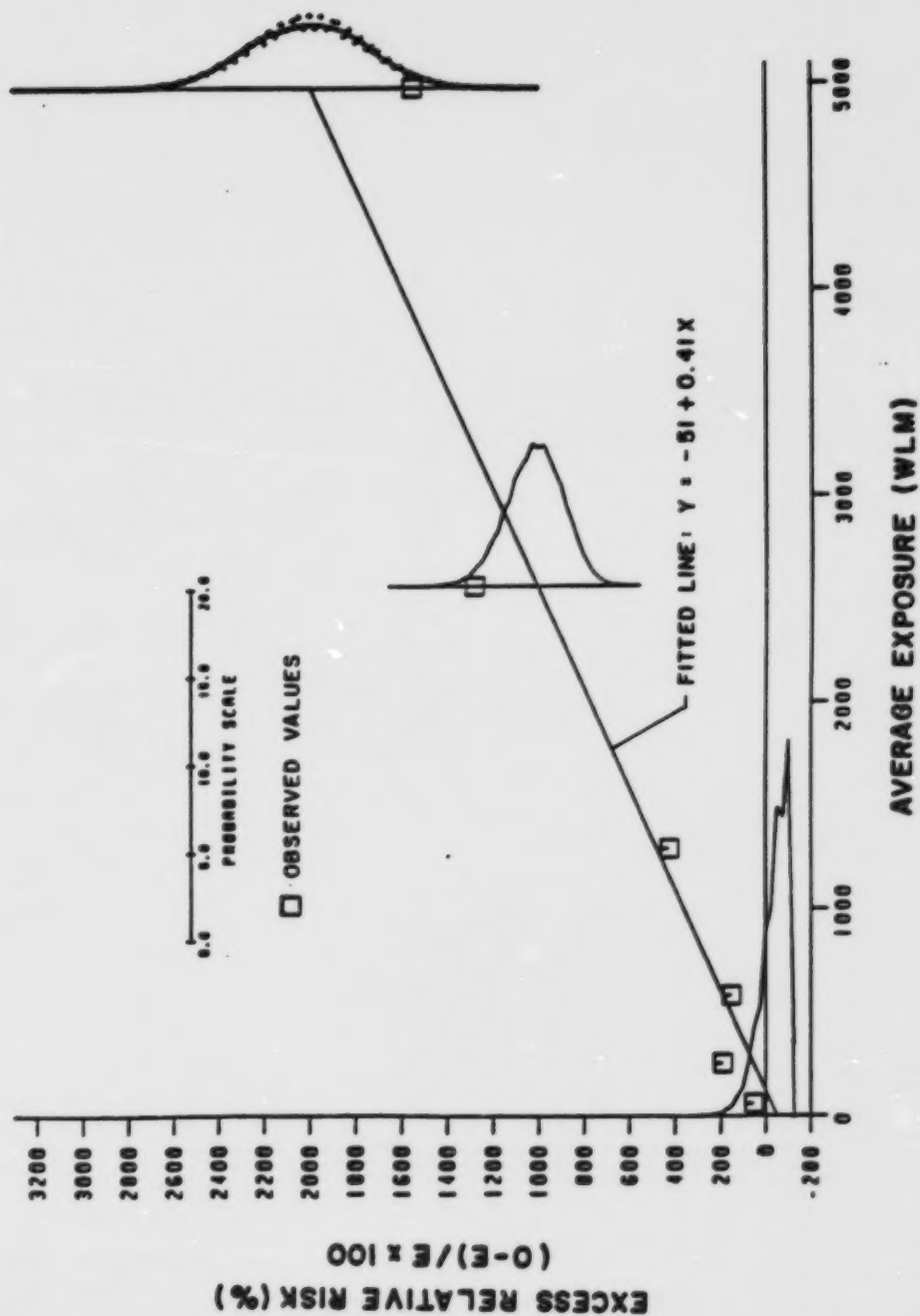


FIGURE 4.6b
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)
 RELATIVE RISK MODEL, U.S. MINERS WITH EXPOSURES PRIOR TO 1950
 (SEE TABLE 4.3)

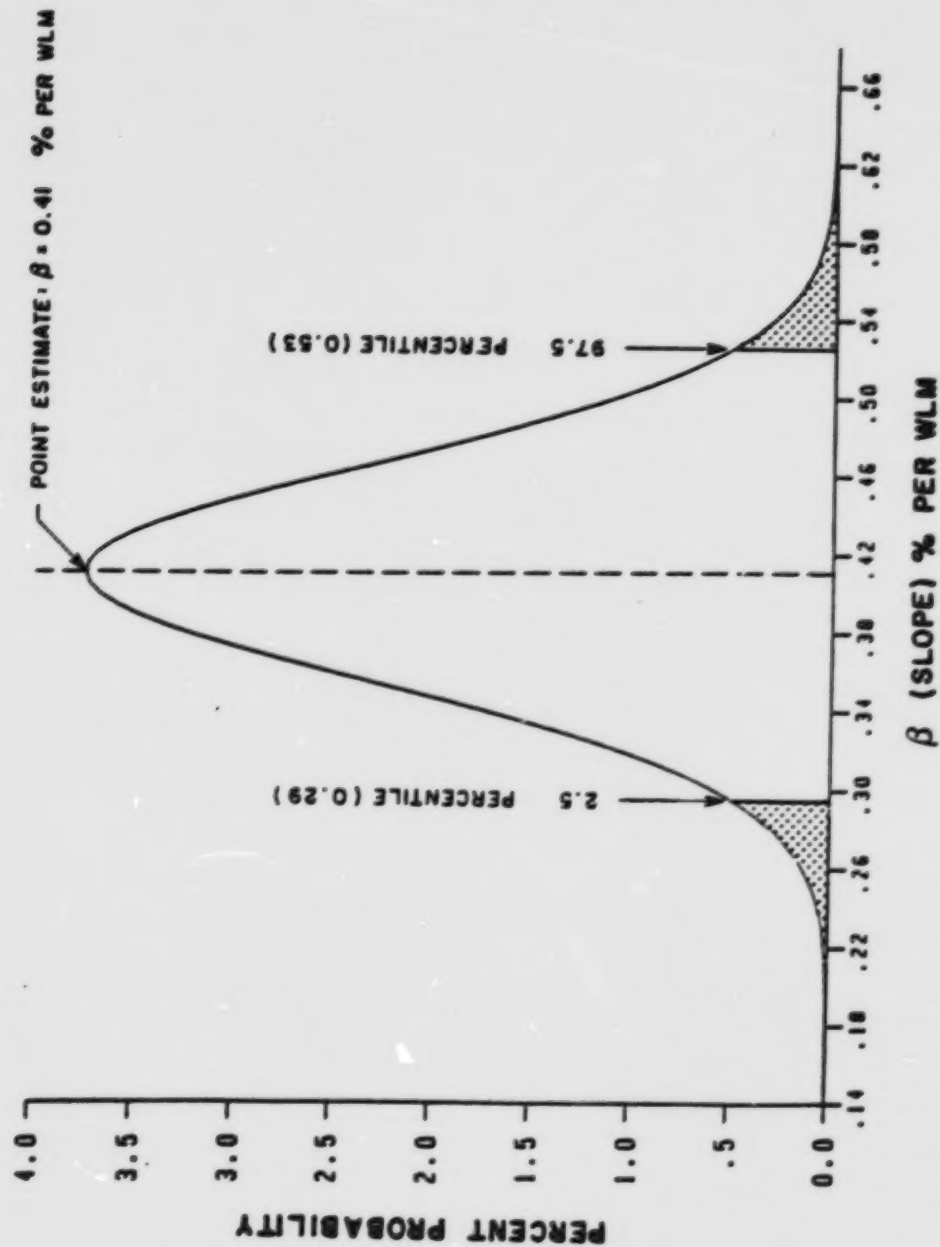


FIGURE 4.7a
INCIDENCE OF LUNG CANCER FOR U.S. URANIUM MINERS WITH NO PRE -1960 EXPOSURE
ABSOLUTE RISK MODEL
(SEE TABLE 4.4)

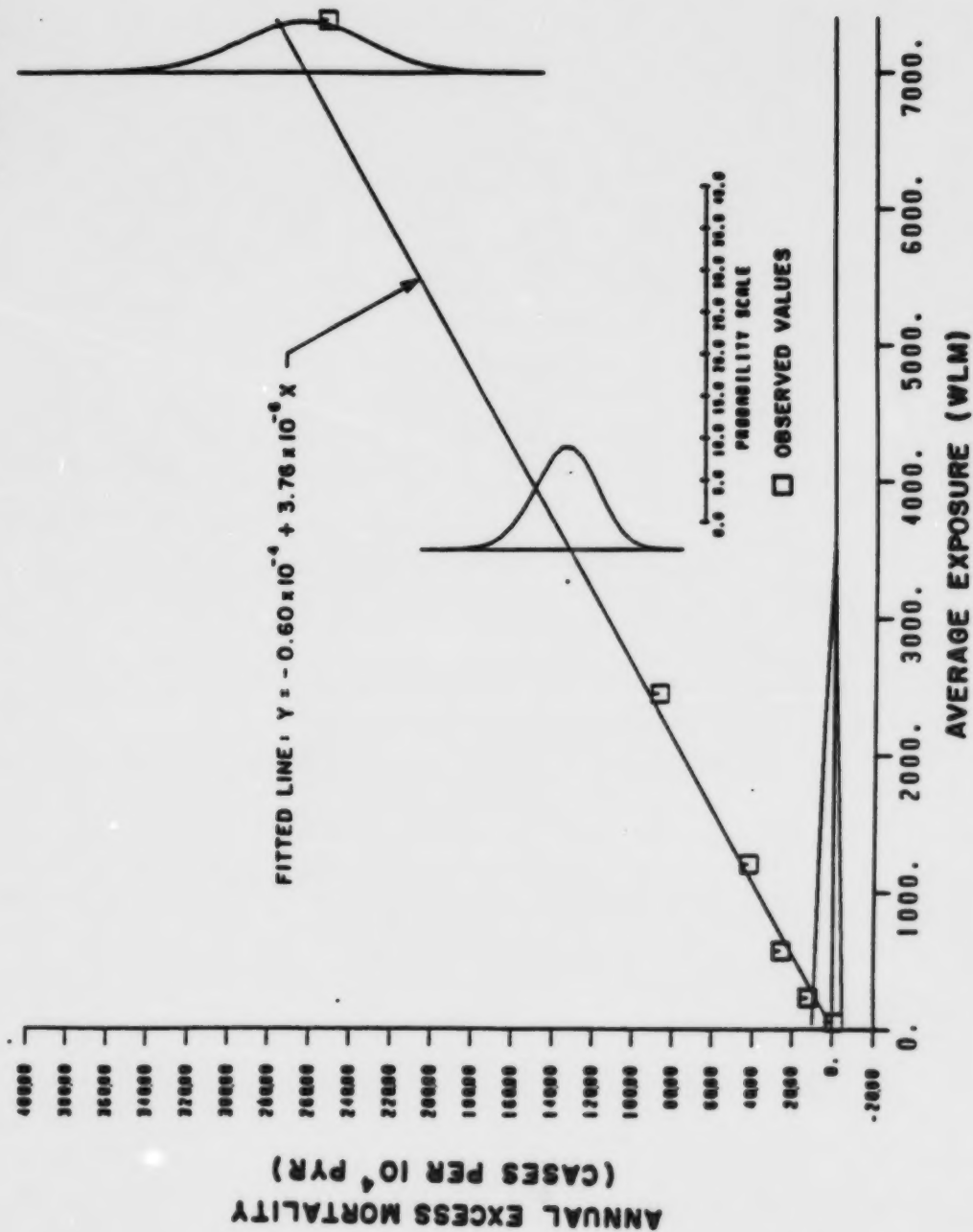


FIGURE 4.7b

MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)

ABSOLUTE RISK MODEL, U.S. URANIUM MINERS WITH NO PRE - 1960 EXPOSURE

(SEE TABLE 4.4)

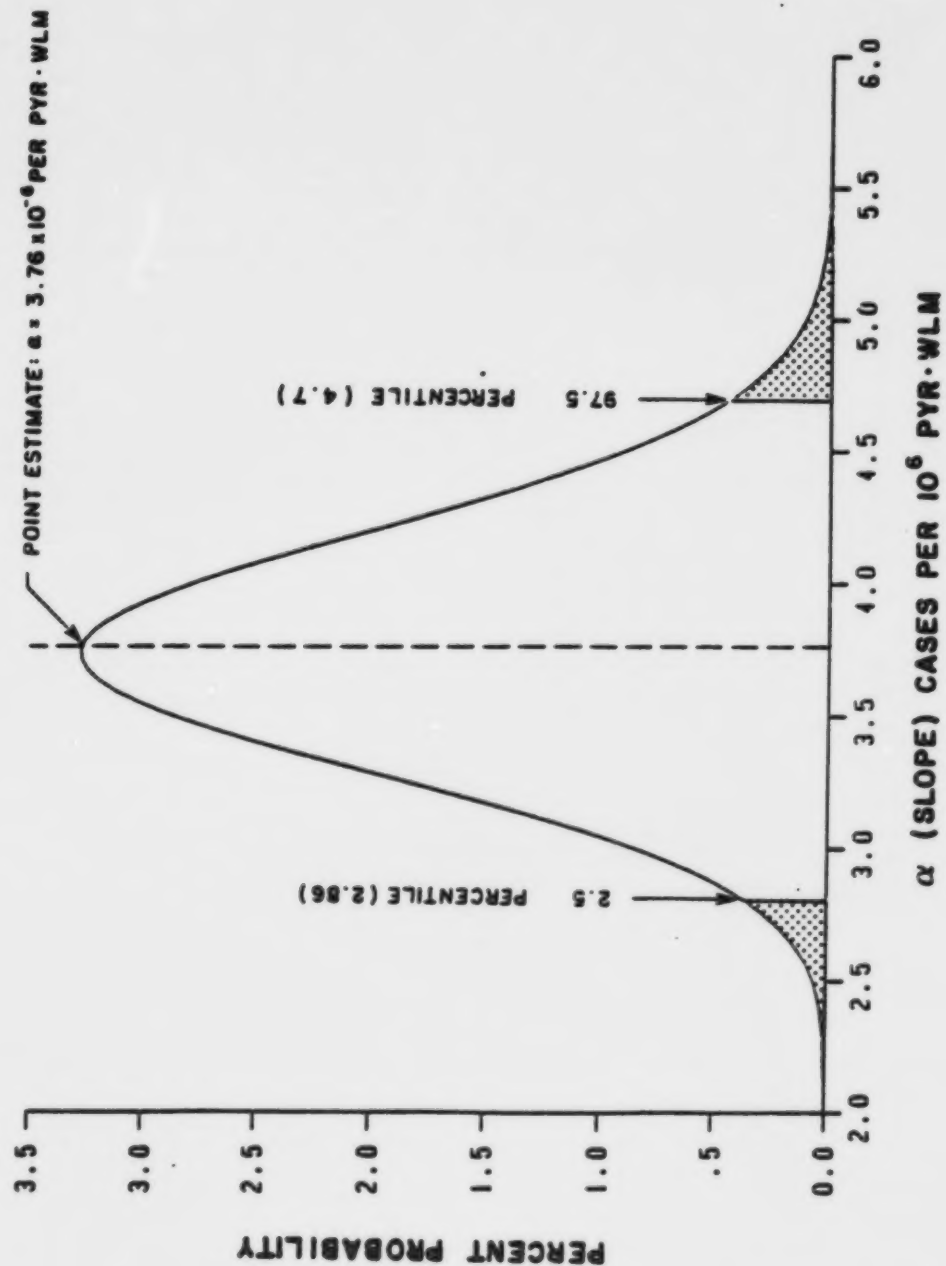


FIGURE 4.8a
INCIDENCE OF LUNG CANCER FOR U.S. URANIUM MINERS WITH NO PRE-1950 EXPOSURE
RELATIVE RISK MODEL
(SEE TABLE 4.4)

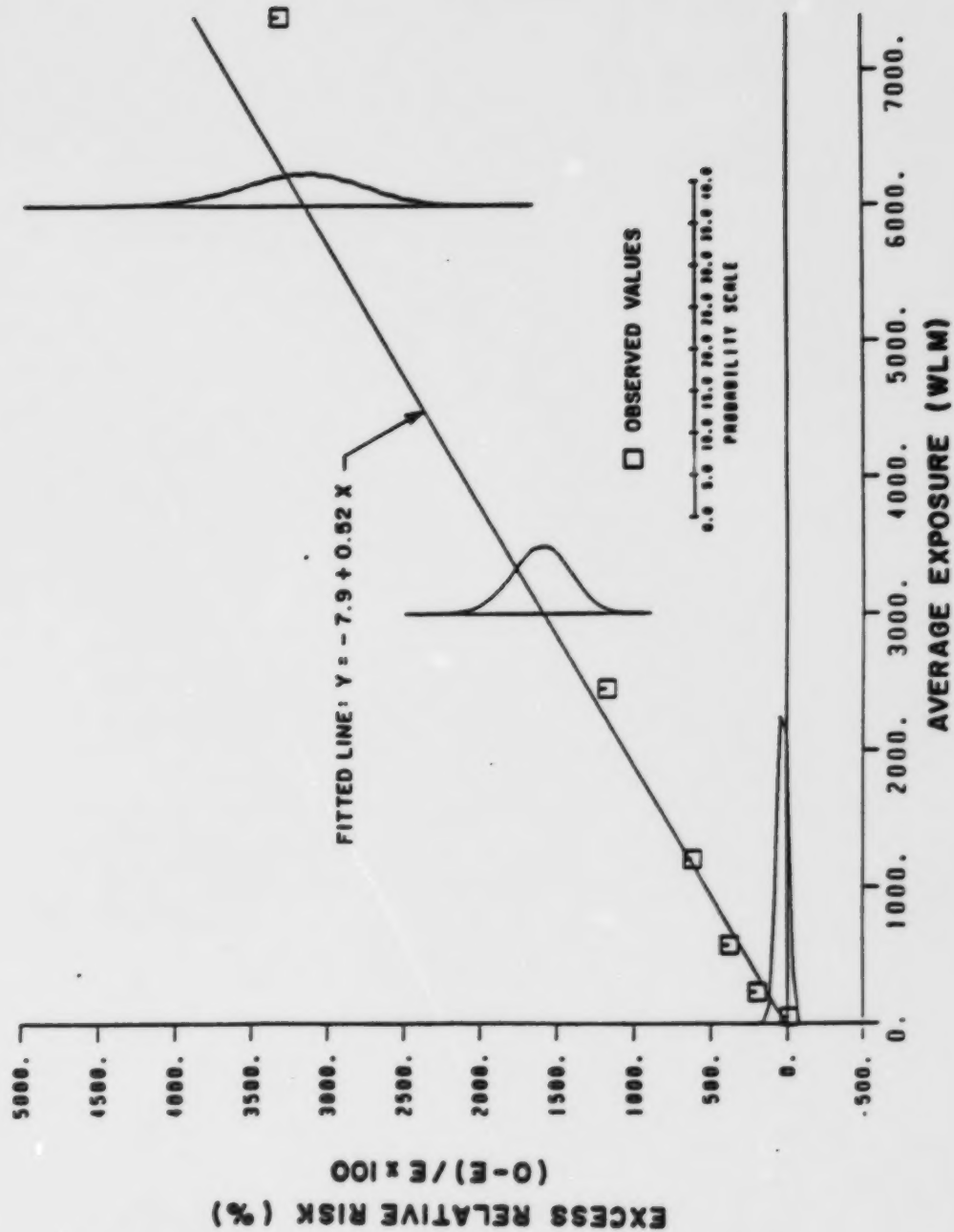


FIGURE 4.8b
MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)
RELATIVE RISK MODEL, U.S. URANIUM MINERS WITH NO PRE-1950 EXPOSURE
(SEE TABLE 4.4)

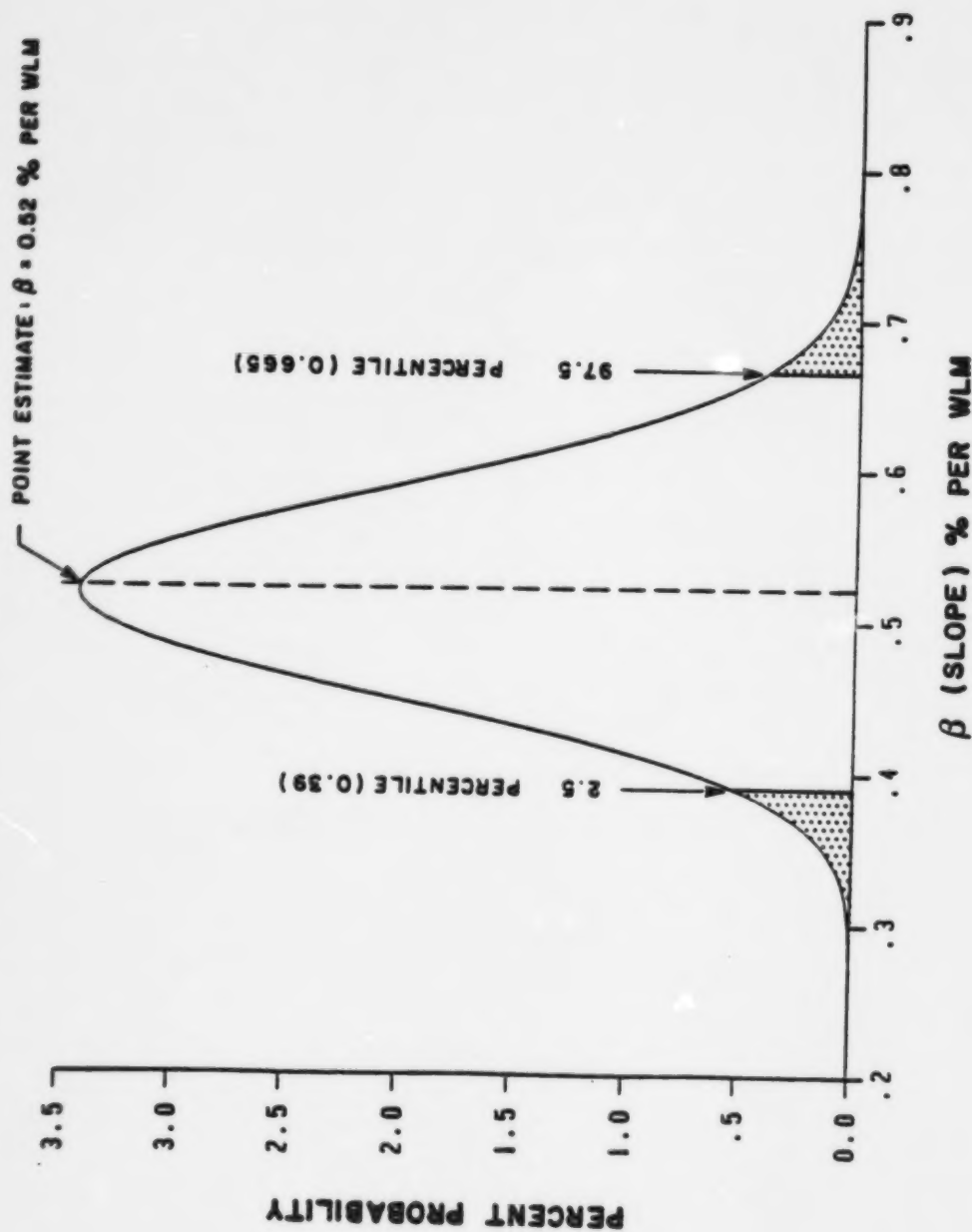


FIGURE 4.9a
INCIDENCE OF LUNG CANCER FOR ONTARIO URANIUM MINERS
WITH NO GOLD MINING EXPERIENCE
ABSOLUTE RISK MODEL (SEE TABLE 4.5)

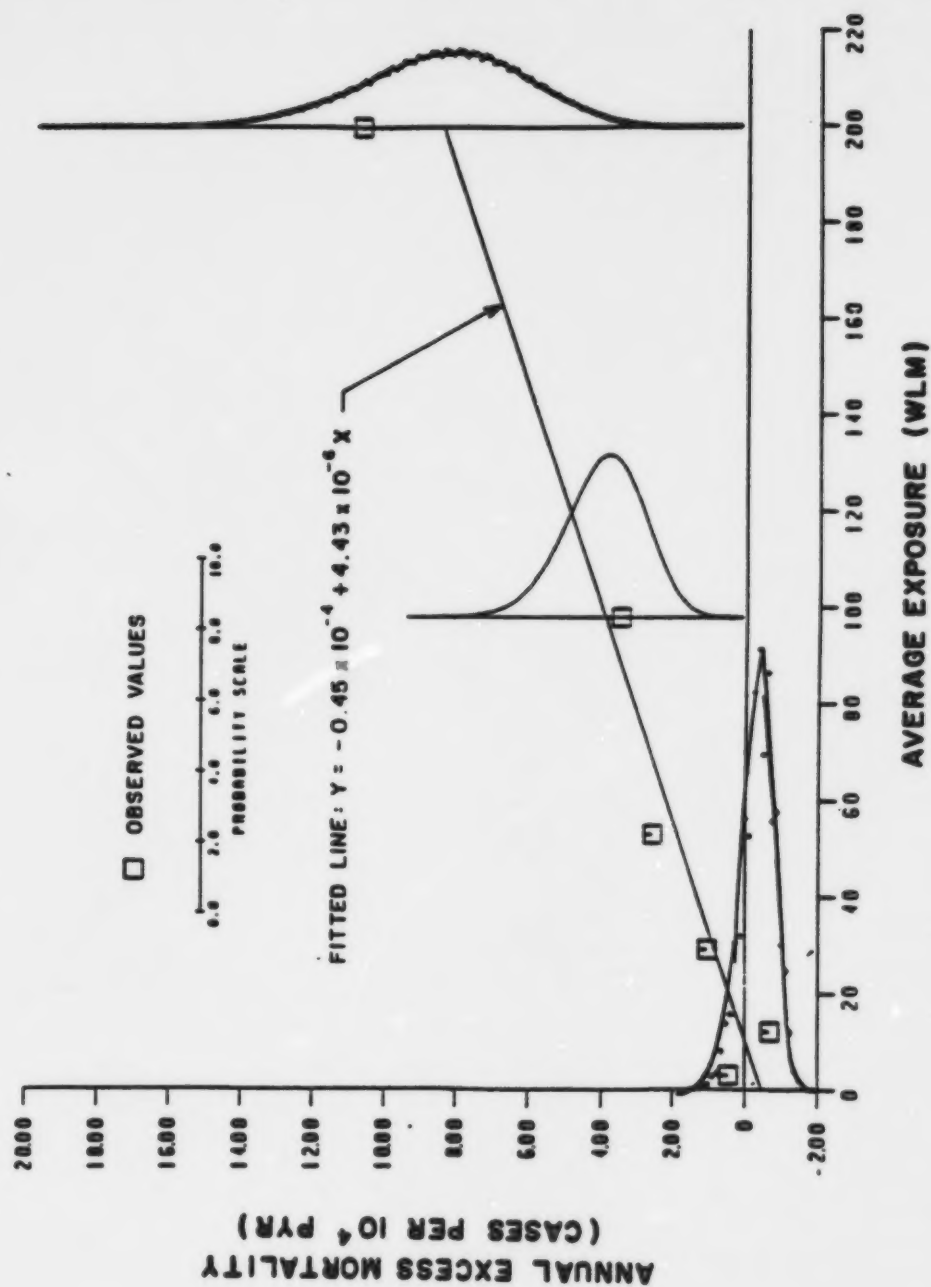


FIGURE 4.9b

MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)

ONTARIO URANIUM MINERS WITH NO GOLD MINING EXPERIENCE

ABSOLUTE RISK MODEL (SEE TABLE 4.5)

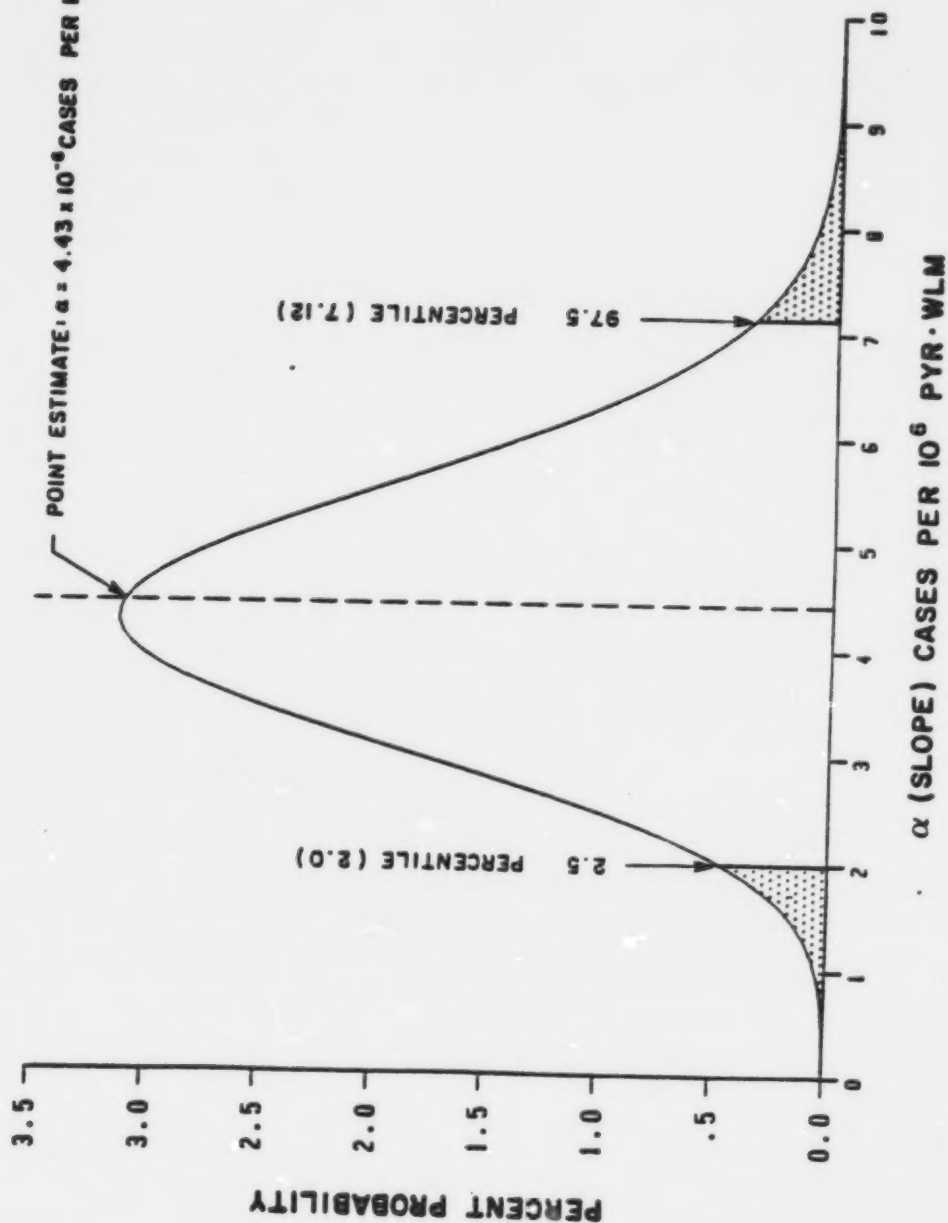


FIGURE 4.10a

INCIDENCE OF LUNG CANCER FOR ONTARIO URANIUM MINERS
WITH NO GOLD MINING EXPERIENCE
RELATIVE RISK MODEL (SEE TABLE 4.5)

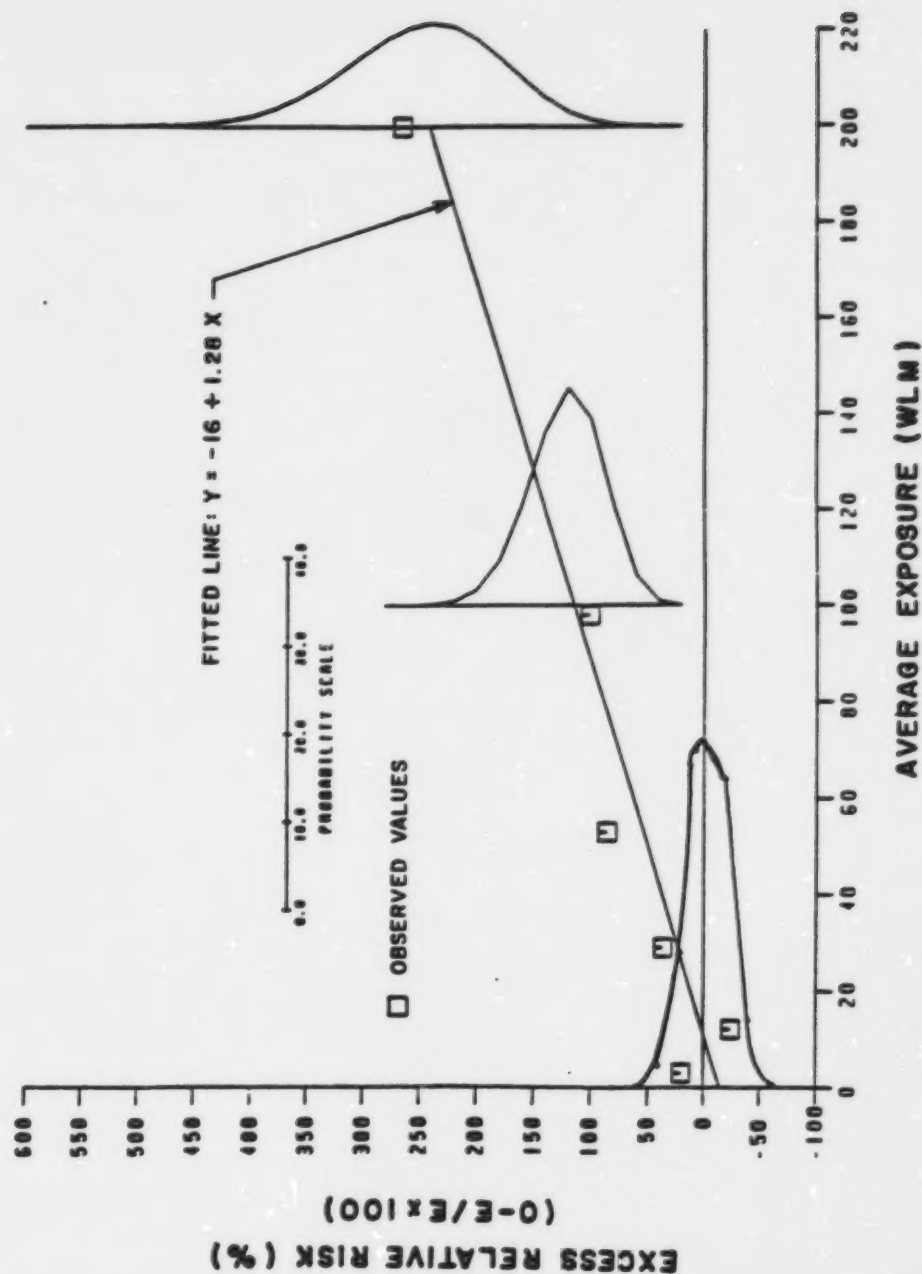


FIGURE 4.10b

MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)

ONTARIO URANIUM MINERS WITH NO GOLD MINING EXPERIENCE

RELATIVE RISK MODEL (SEE TABLE 4.5)

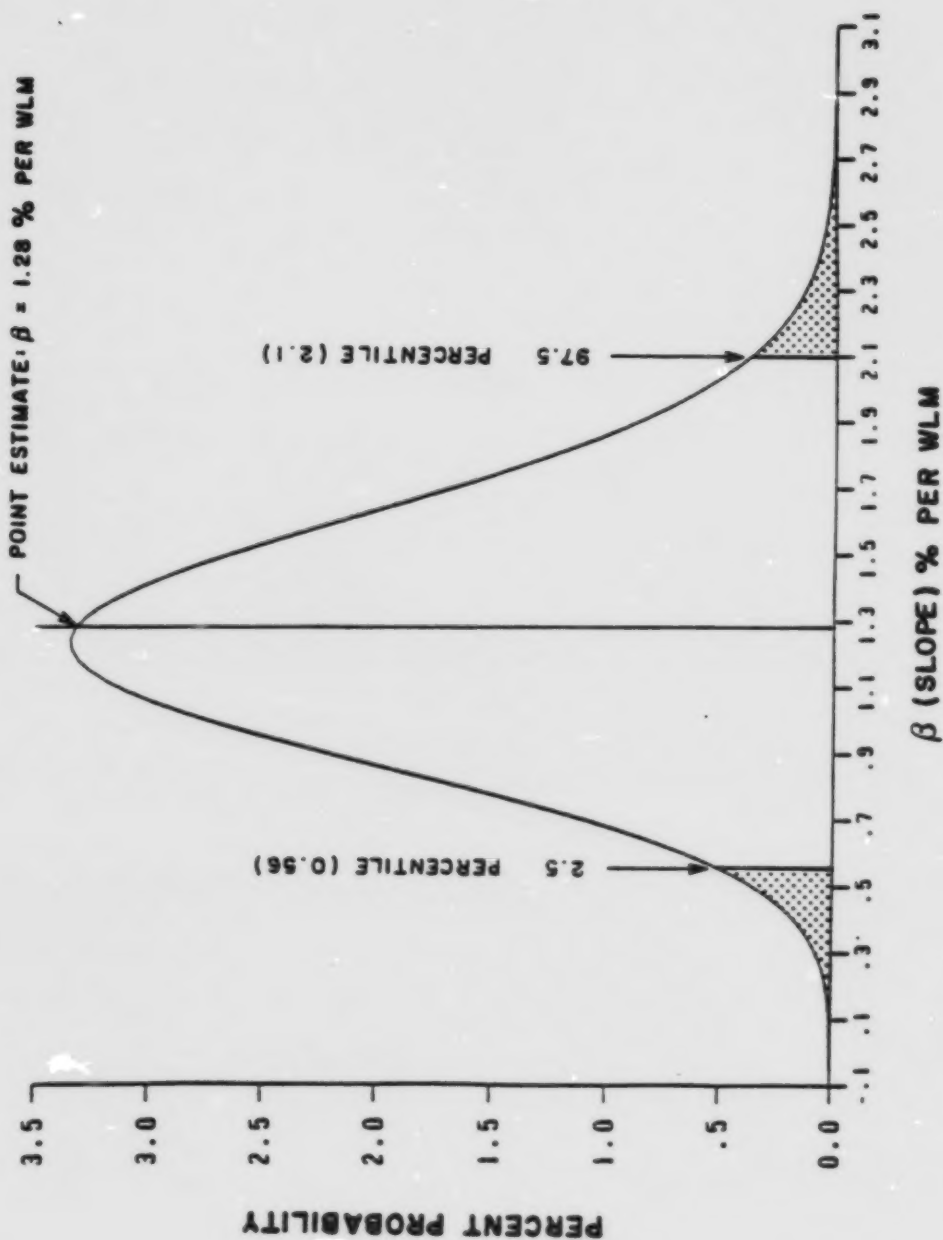


FIGURE 4.11a
INCIDENCE OF LUNG CANCER FOR ONTARIO URANIUM MINERS
WITH GOLD MINING EXPERIENCE
ABSOLUTE RISK MODEL (SEE TABLE 4.6)

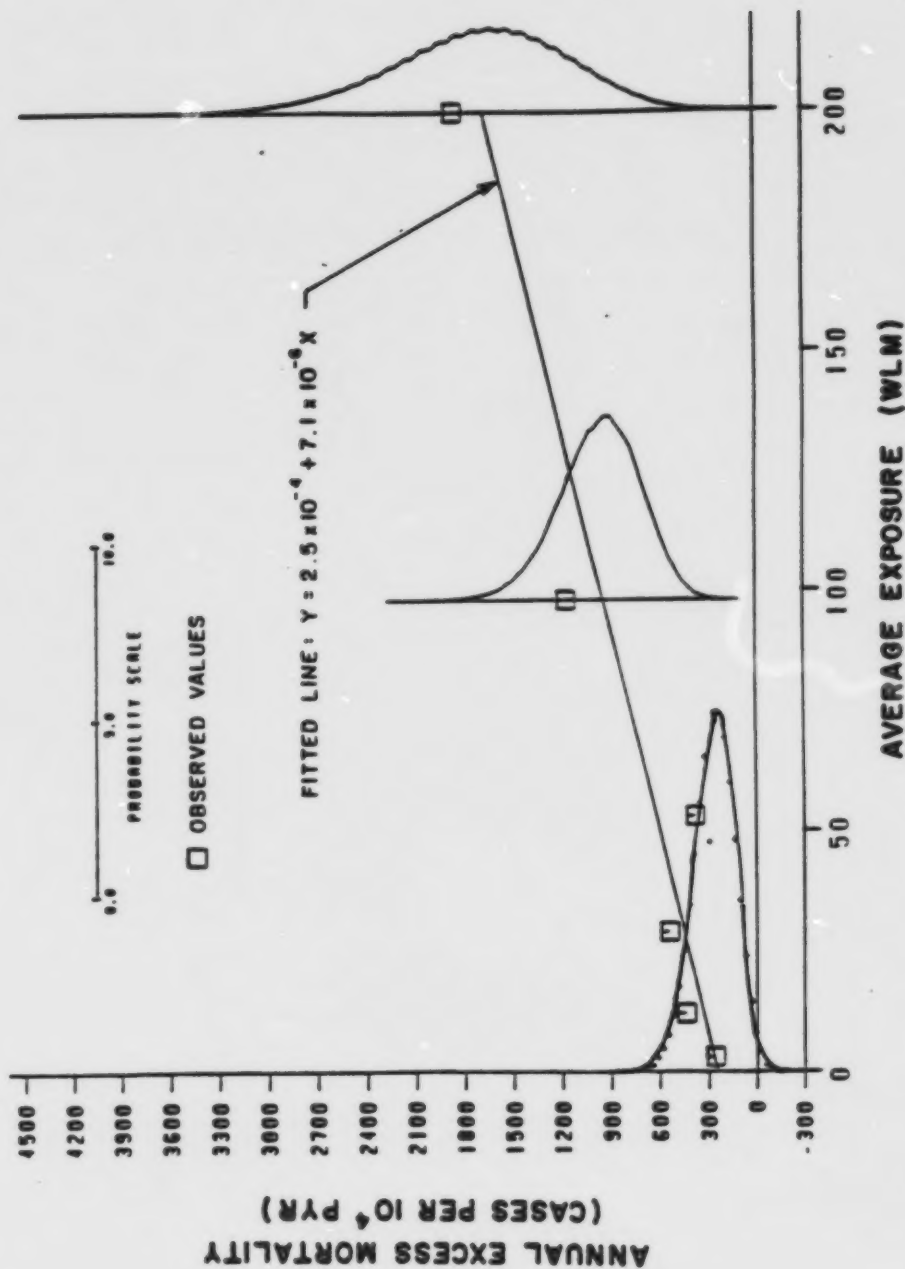


FIGURE 4.11b
MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)
ONTARIO URANIUM MINERS WITH GOLD MINING EXPERIENCE
ABSOLUTE RISK MODEL (SEE TABLE 4.6)

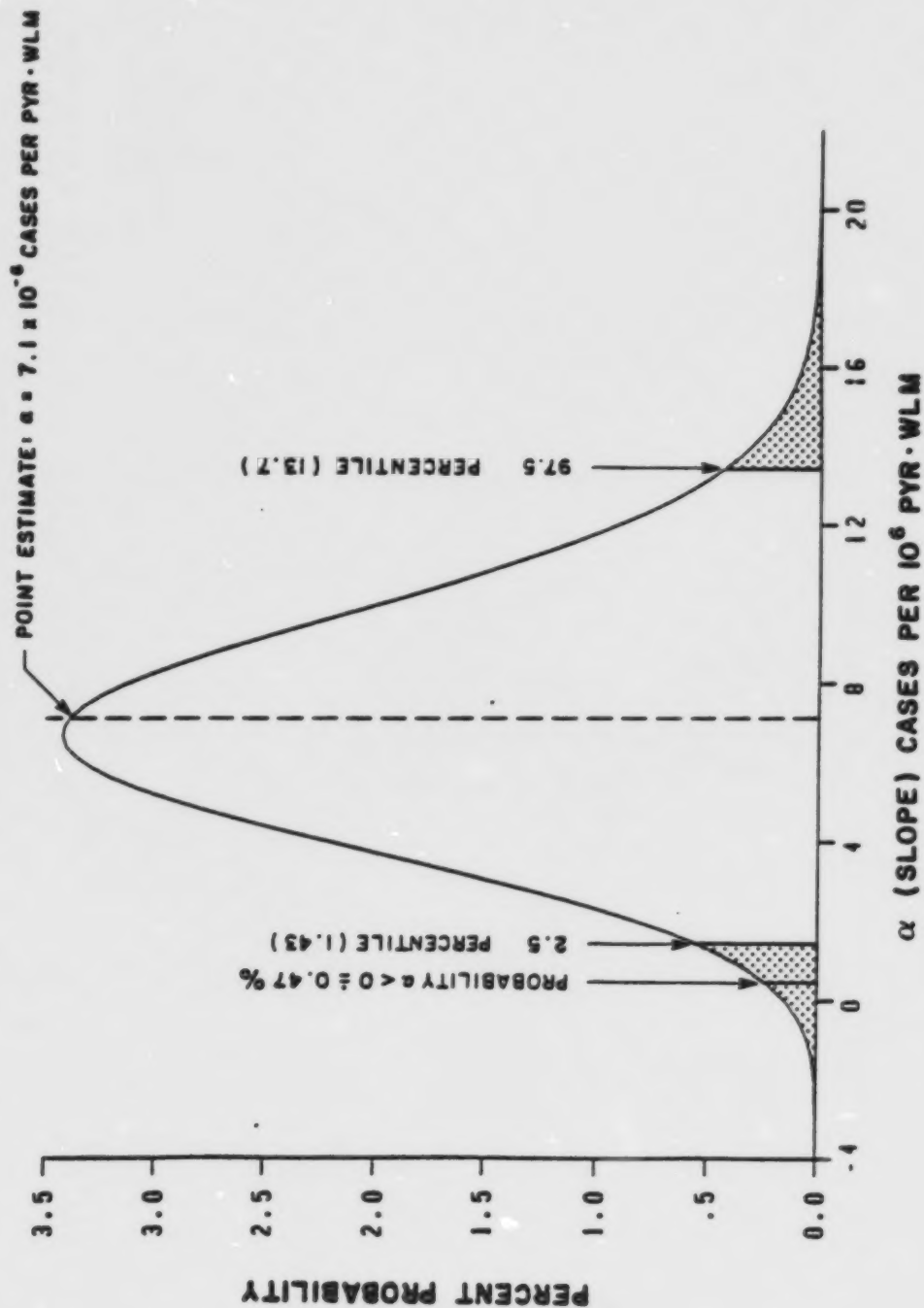


FIGURE 4.12a
INCIDENCE OF LUNG CANCER FOR ONTARIO URANIUM MINERS
WITH GOLD MINING EXPERIENCE
RELATIVE RISK MODEL (SEE TABLE 4.6)

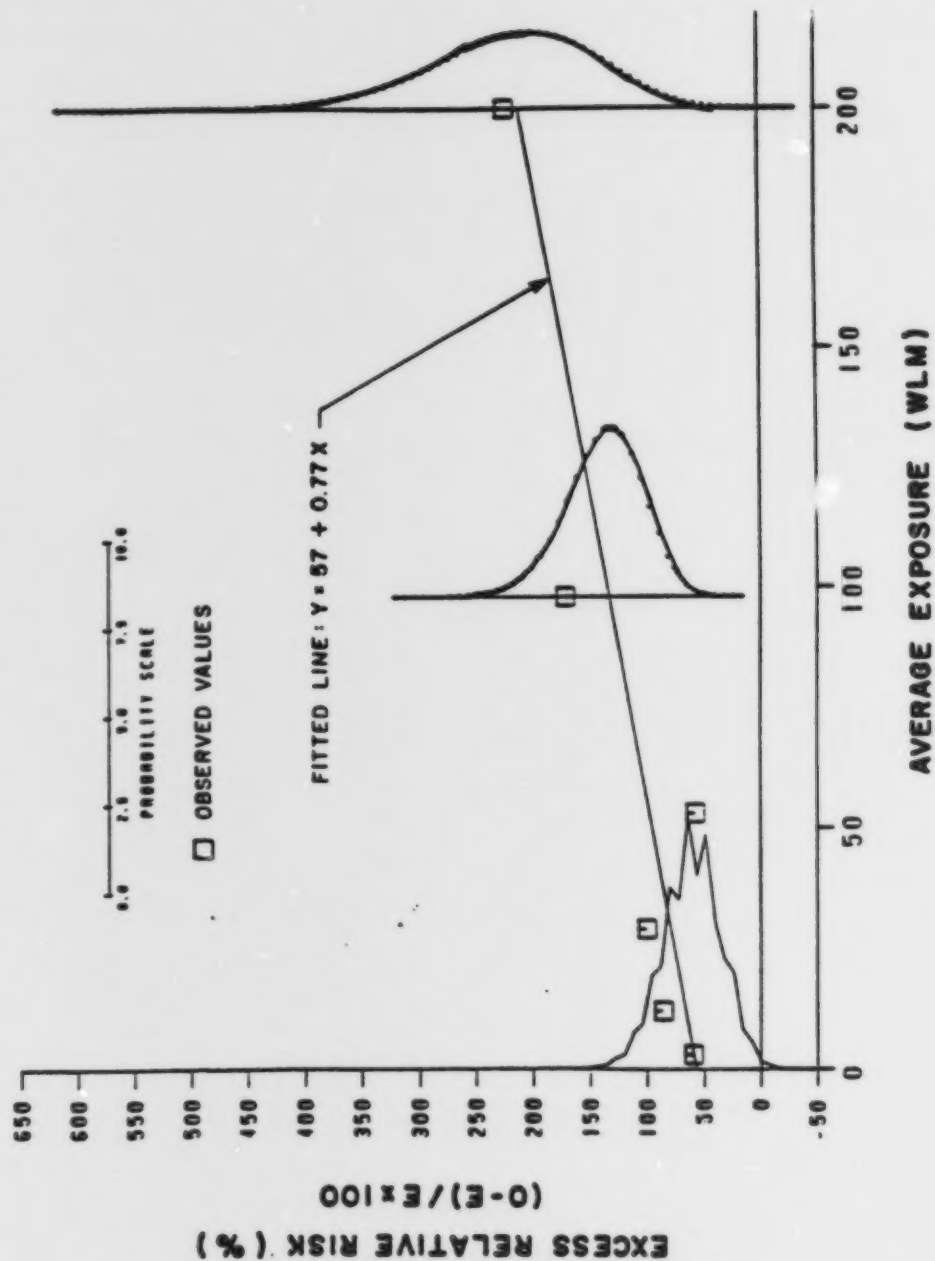


FIGURE 4.12b
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)
 ONTARIO URANIUM MINERS WITH GOLD MINING EXPERIENCE
 RELATIVE RISK MODEL (SEE TABLE 4.6)

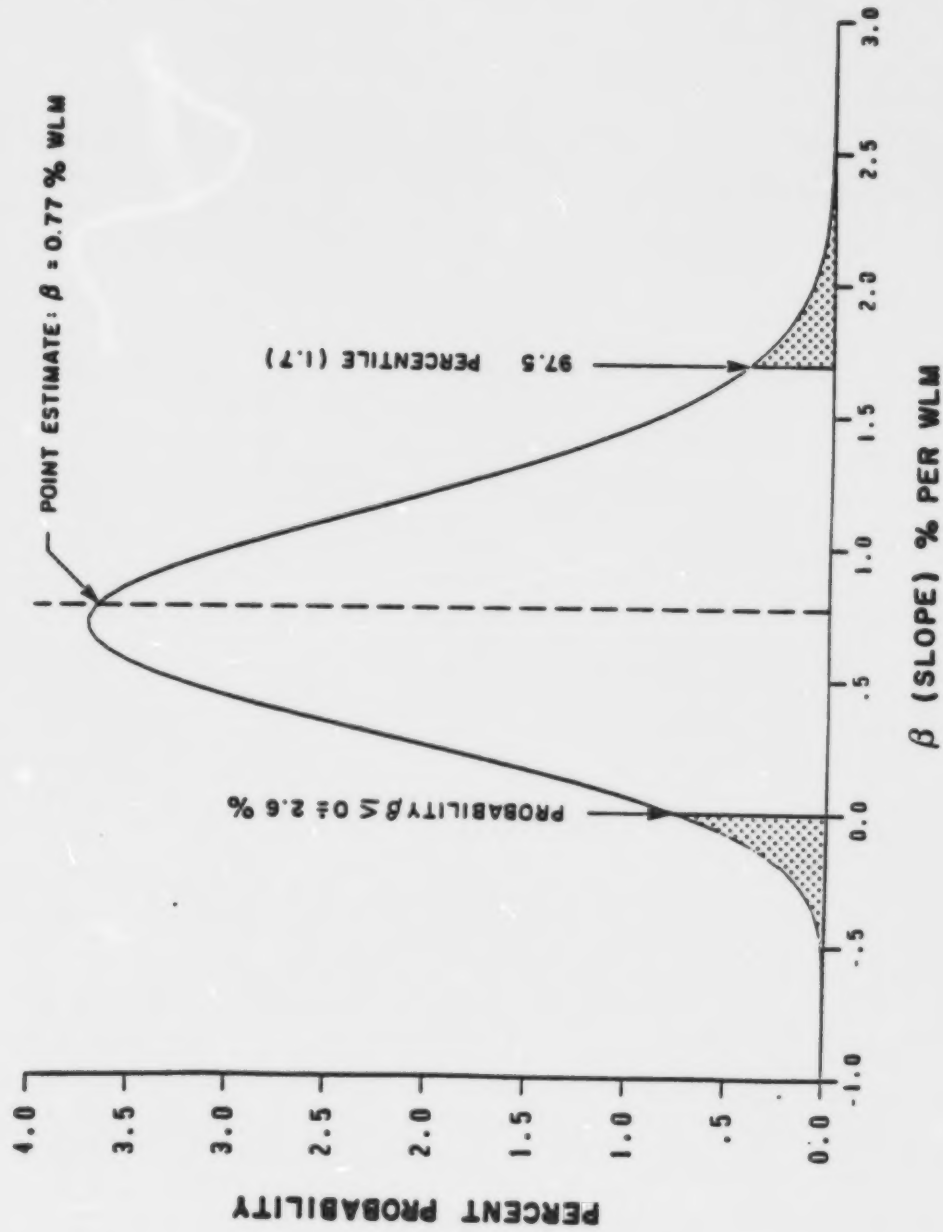


FIGURE 4.13a

MARGINAL PROBABILITY DISTRIBUTIONS OF INTERCEPTS (α_0)
FOR ONTARIO URANIUM MINERS
ABSOLUTE RISK MODEL

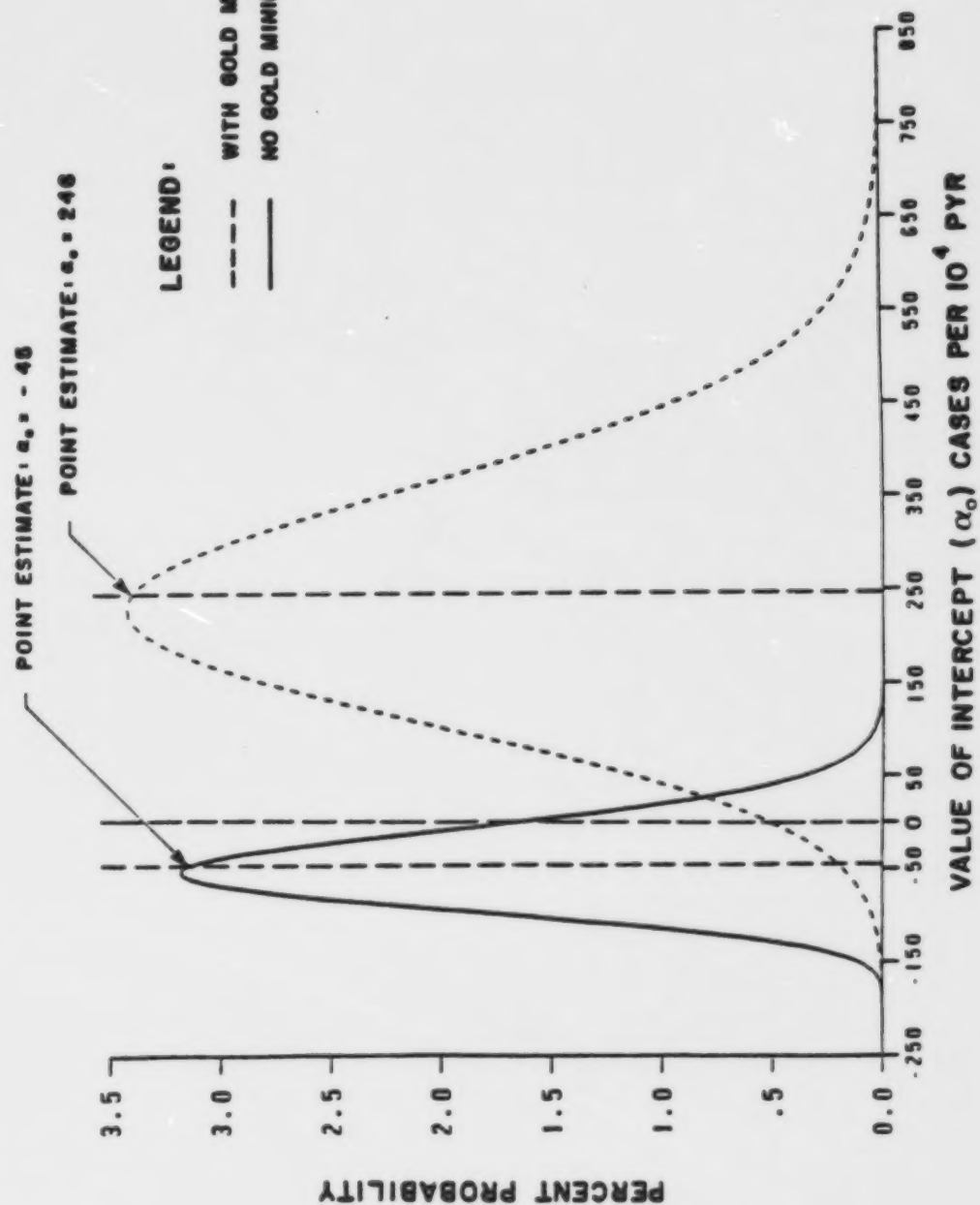


FIGURE 4.13b
MARGINAL PROBABILITY DISTRIBUTION FOR DIFFERENCE BETWEEN INTERCEPTS (α_0)
ONTARIO URANIUM MINERS(WITH/NO) GOLD MINING EXPERIENCE
ABSOLUTE RISK MODEL

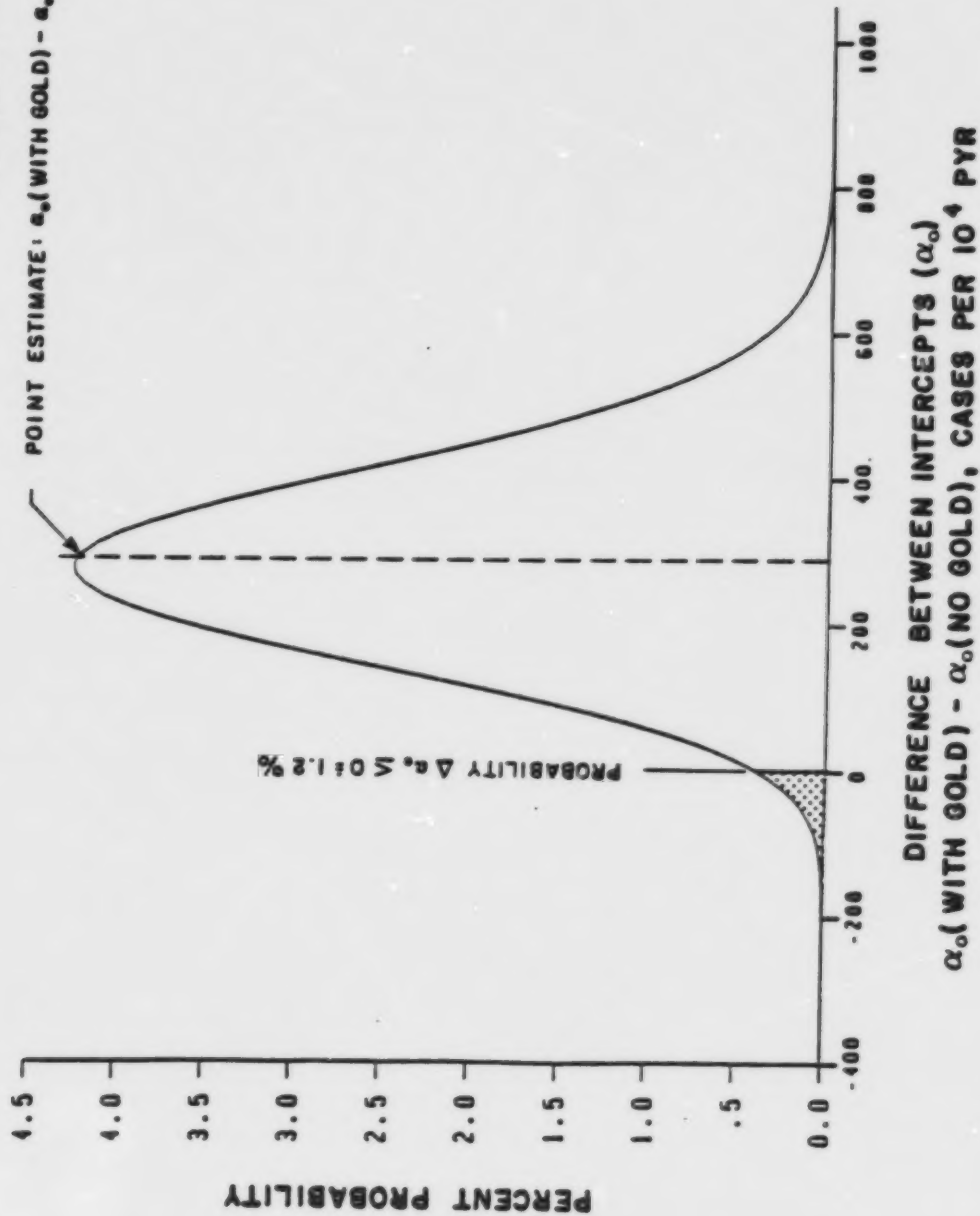


FIGURE 4.14a

MARGINAL PROBABILITY DISTRIBUTIONS OF INTERCEPTS (β_0)
FOR ONTARIO URANIUM MINERS
RELATIVE RISK MODEL

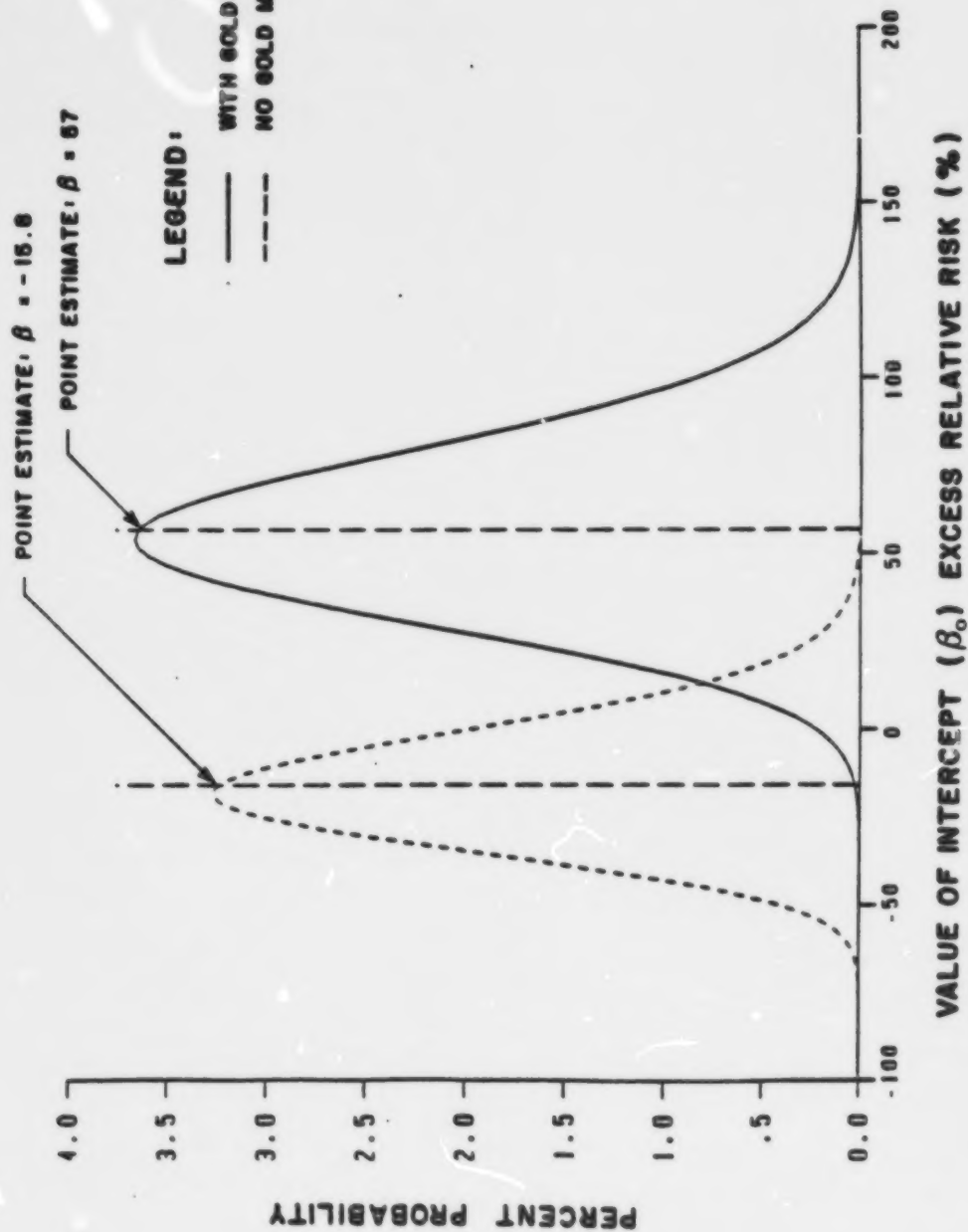


FIGURE 4.14b

MARGINAL PROBABILITY DISTRIBUTION FOR DIFFERENCE BETWEEN INTERCEPTS (β_0)
 ONTARIO URANIUM MINERS (WITH/NO) GOLD MINING EXPERIENCE
 RELATIVE RISK MODEL

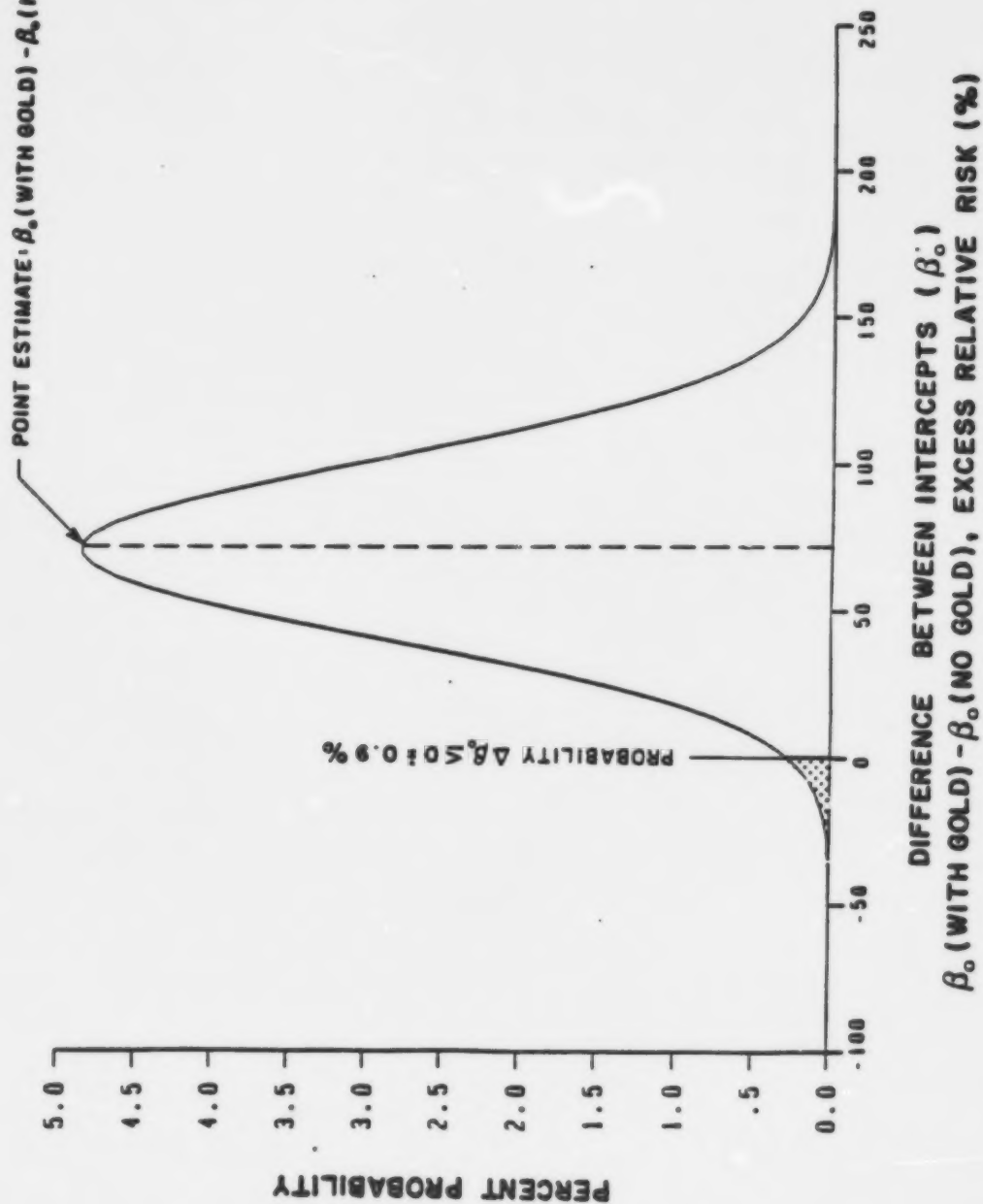
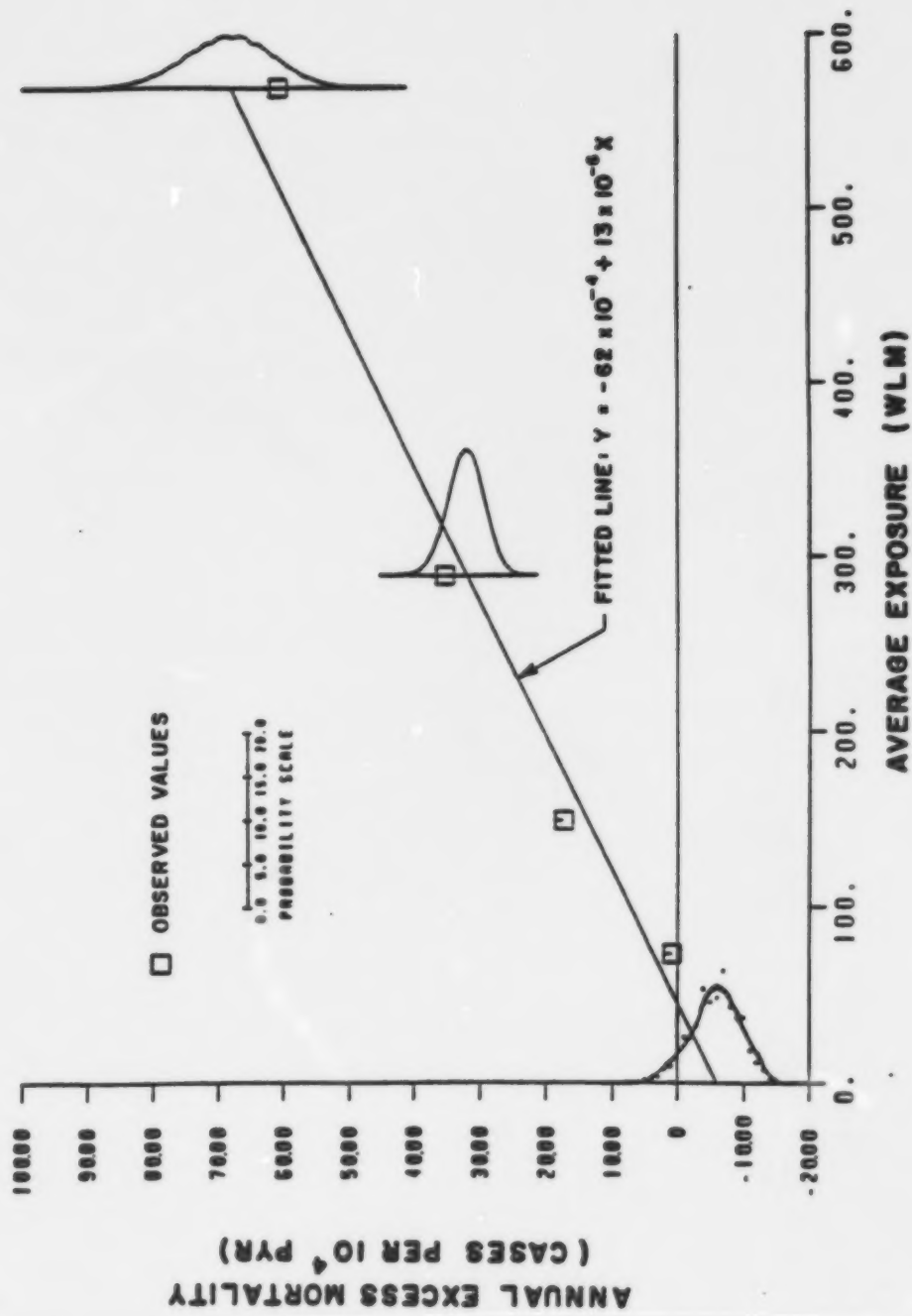


FIGURE 4.15 a
INCIDENCE OF LUNG CANCER FOR CZECHOSLOVAKIAN URANIUM MINERS
ABSOLUTE RISK MODEL
(SEE TABLE 4.7)



4.16 b
MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)
ABSOLUTE RISK MODEL, CZECHOSLOVAKIAN URANIUM MINERS
(SEE TABLE 4.7)

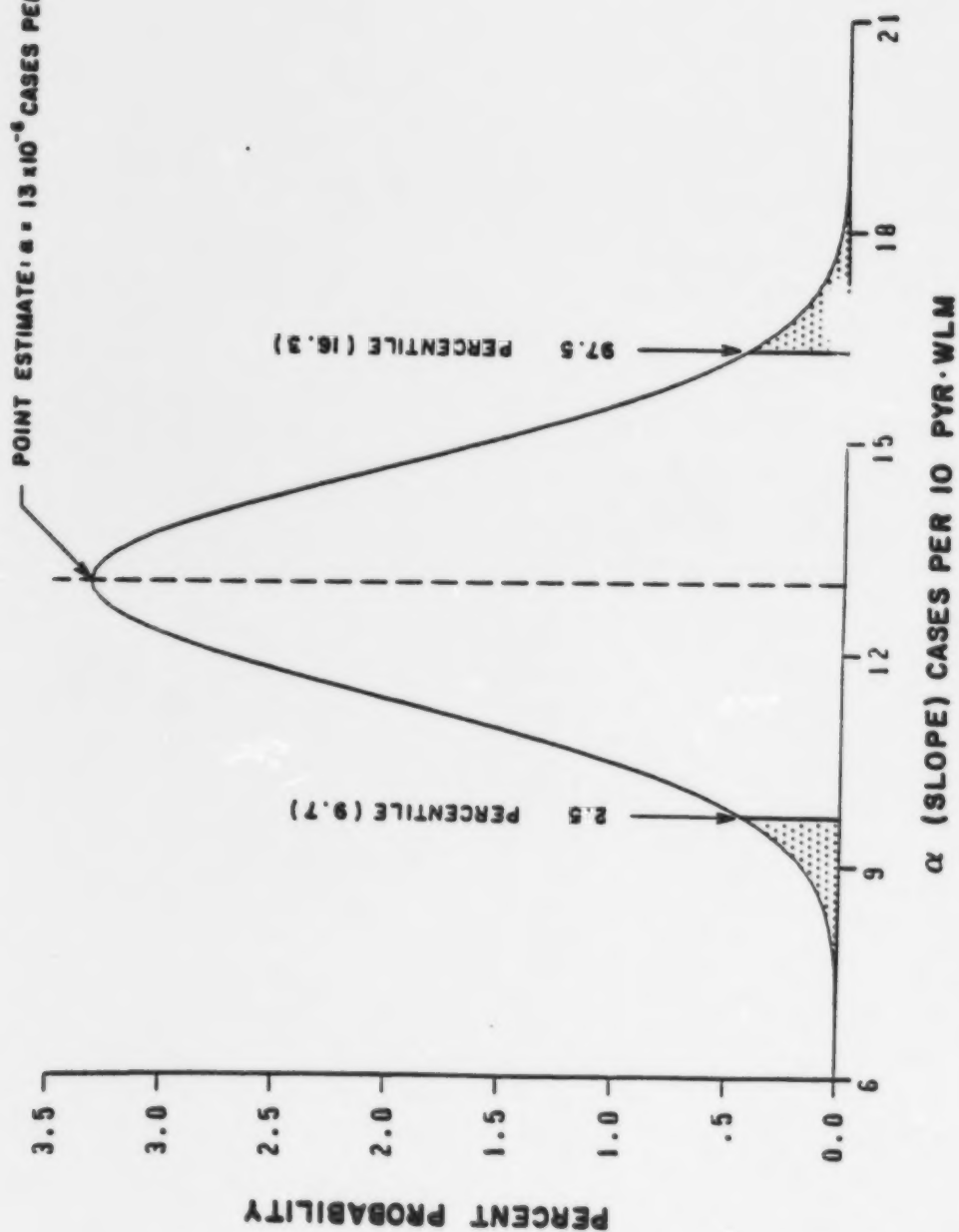


FIGURE 4.16 a
INCIDENCE OF LUNG CANCER FOR CZECHOSLOVAKIAN URANIUM MINERS
RELATIVE RISK MODEL
(SEE TABLE 4.7)

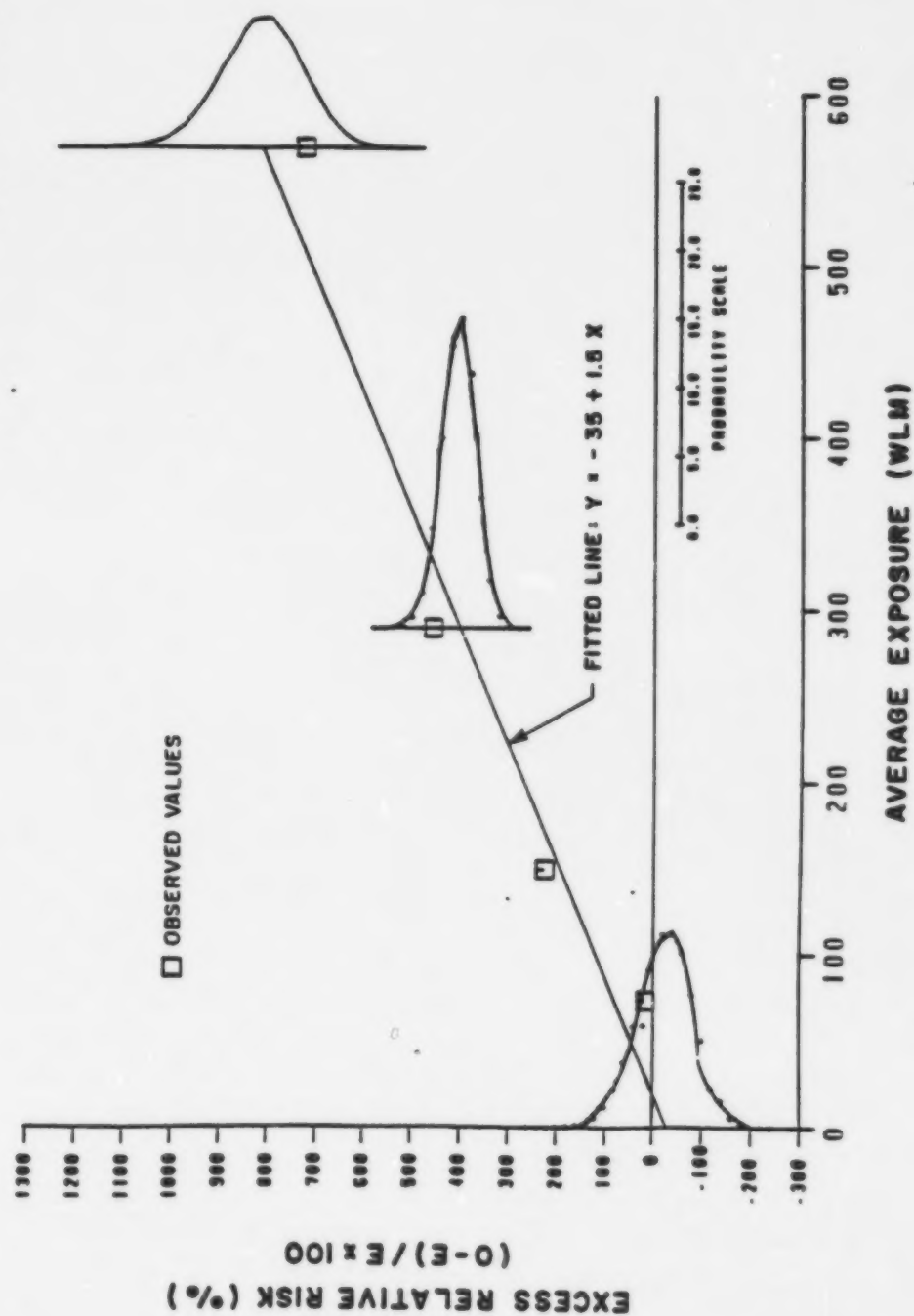


FIGURE 4.16 b
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)
 RELATIVE RISK MODEL, CZECHOSLOVAKIAN URANIUM MINERS
 (SEE TABLE 4.7)

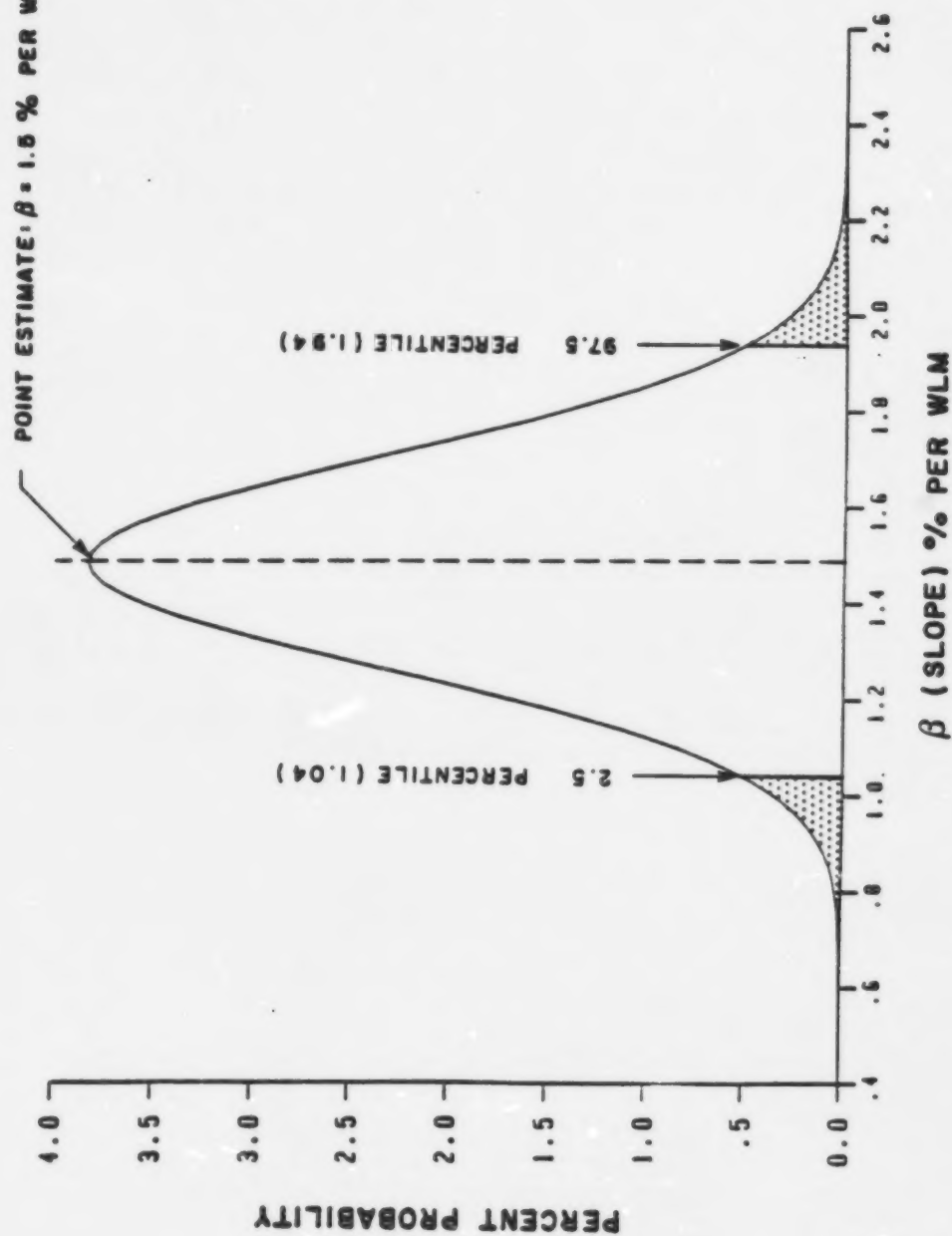


FIGURE 4.17a
INCIDENCE OF LUNG CANCER FOR ELDORADO URANIUM MINERS, BEAVERLODGE
ABSOLUTE RISK MODEL
(SEE TABLE 4.8)

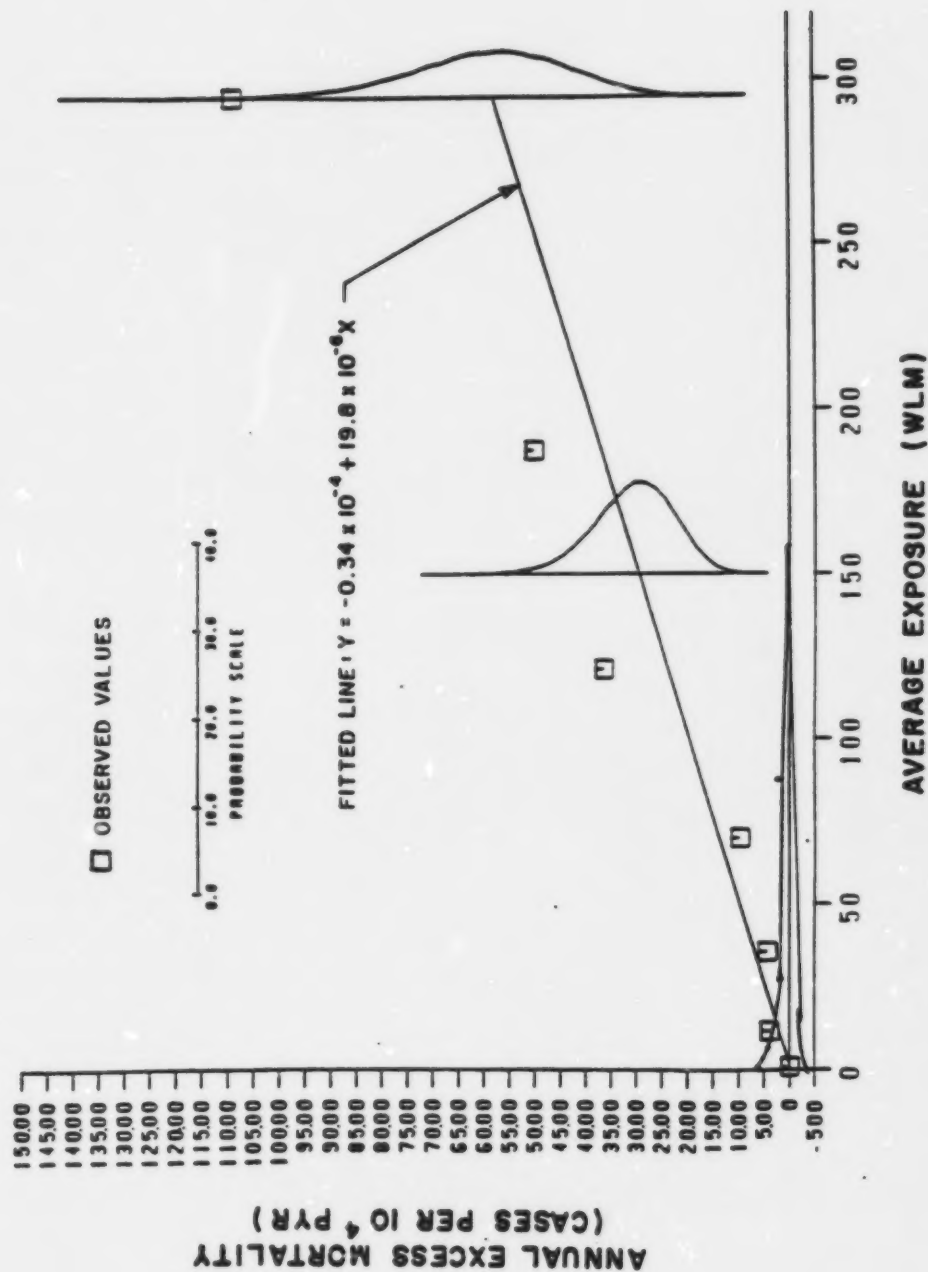


FIGURE 4.17b
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)
 ABSOLUTE RISK MODEL, ELDERADO URANIUM MINERS, BEAVERLODGE
 (SEE TABLE 4.8)

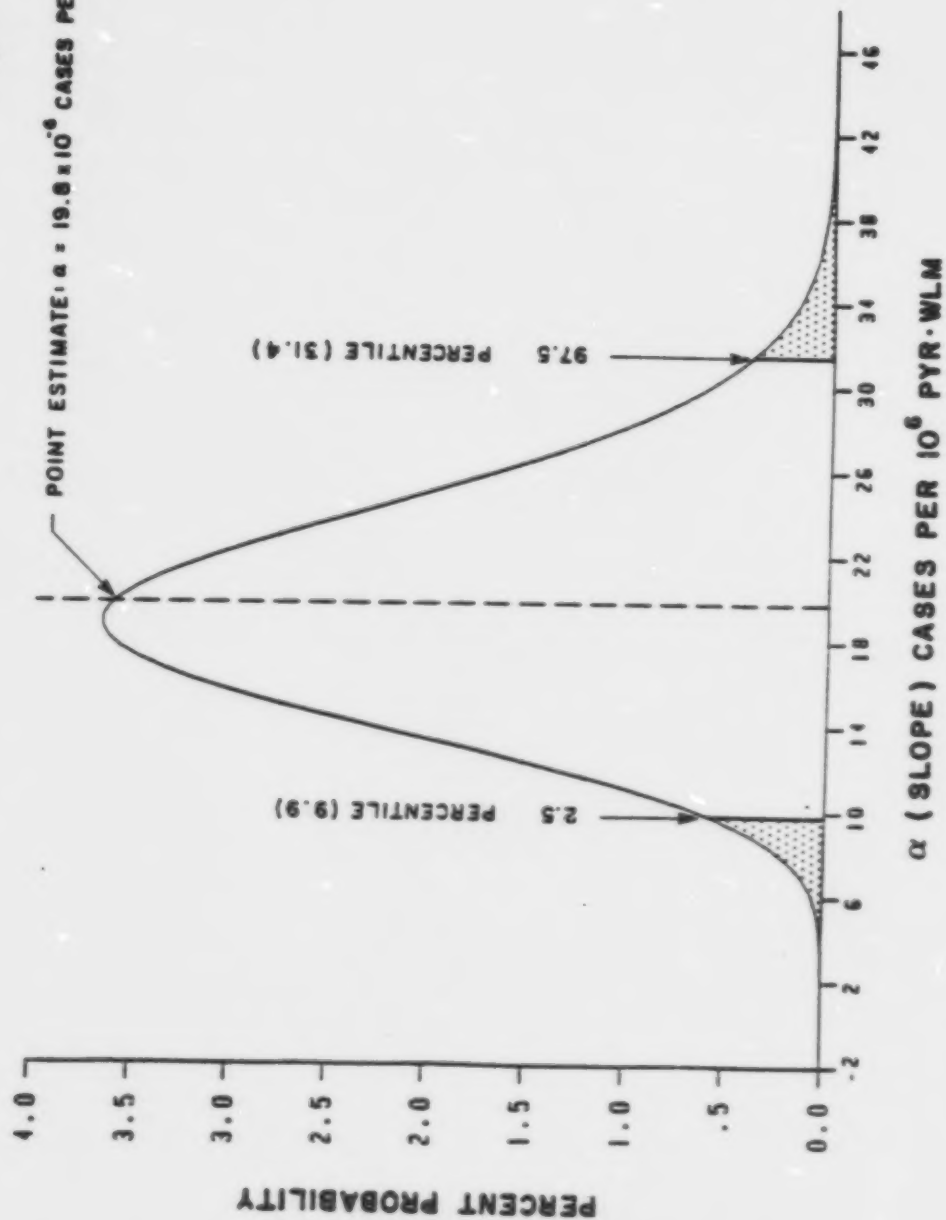


FIGURE 4.18a
INCIDENCE OF LUNG CANCER FOR ELDORADO URANIUM MINERS, BEAVERLODGE
RELATIVE RISK MODEL
(SEE TABLE 4.8)

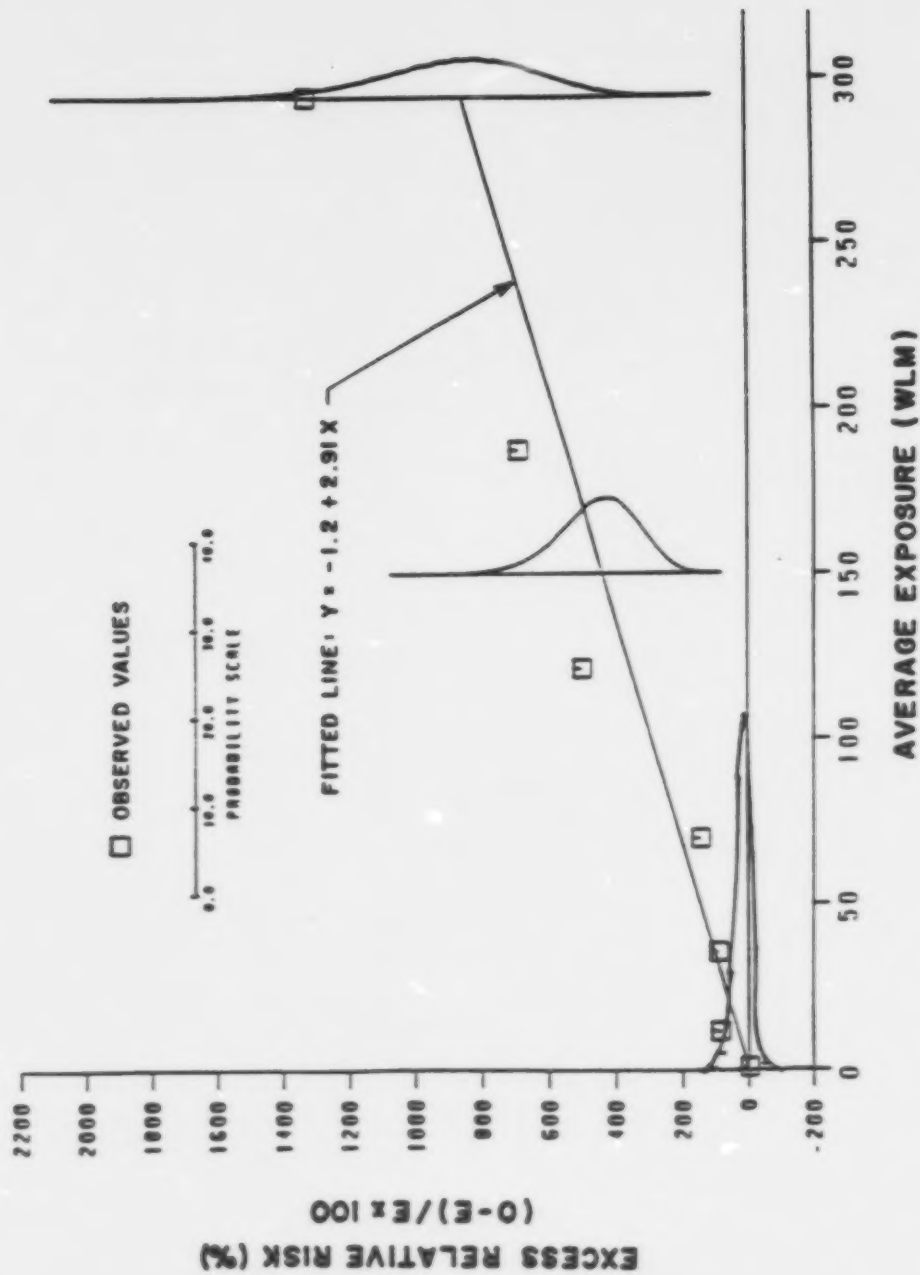


FIGURE 4.18b
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)
 RELATIVE RISK MODEL, ELDORADO URANIUM MINERS, BEAVERLODGE
 (SEE TABLE 4.8)

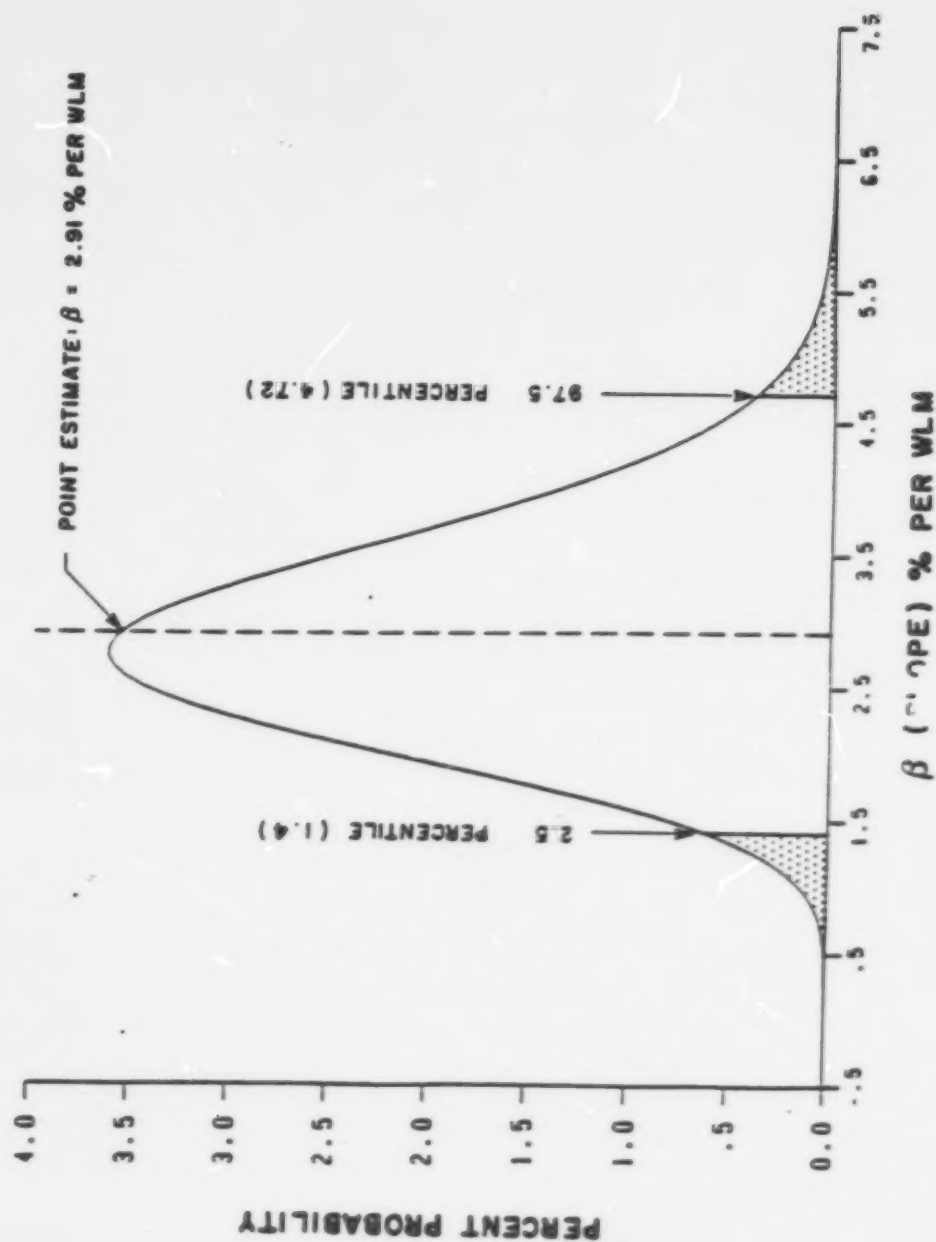


FIGURE 4.19a
INCIDENCE OF LUNG CANCER FOR ELDORADO URANIUM MINERS, PORT RADIUM
ABSOLUTE RISK MODEL
(SEE TABLE 4.9)

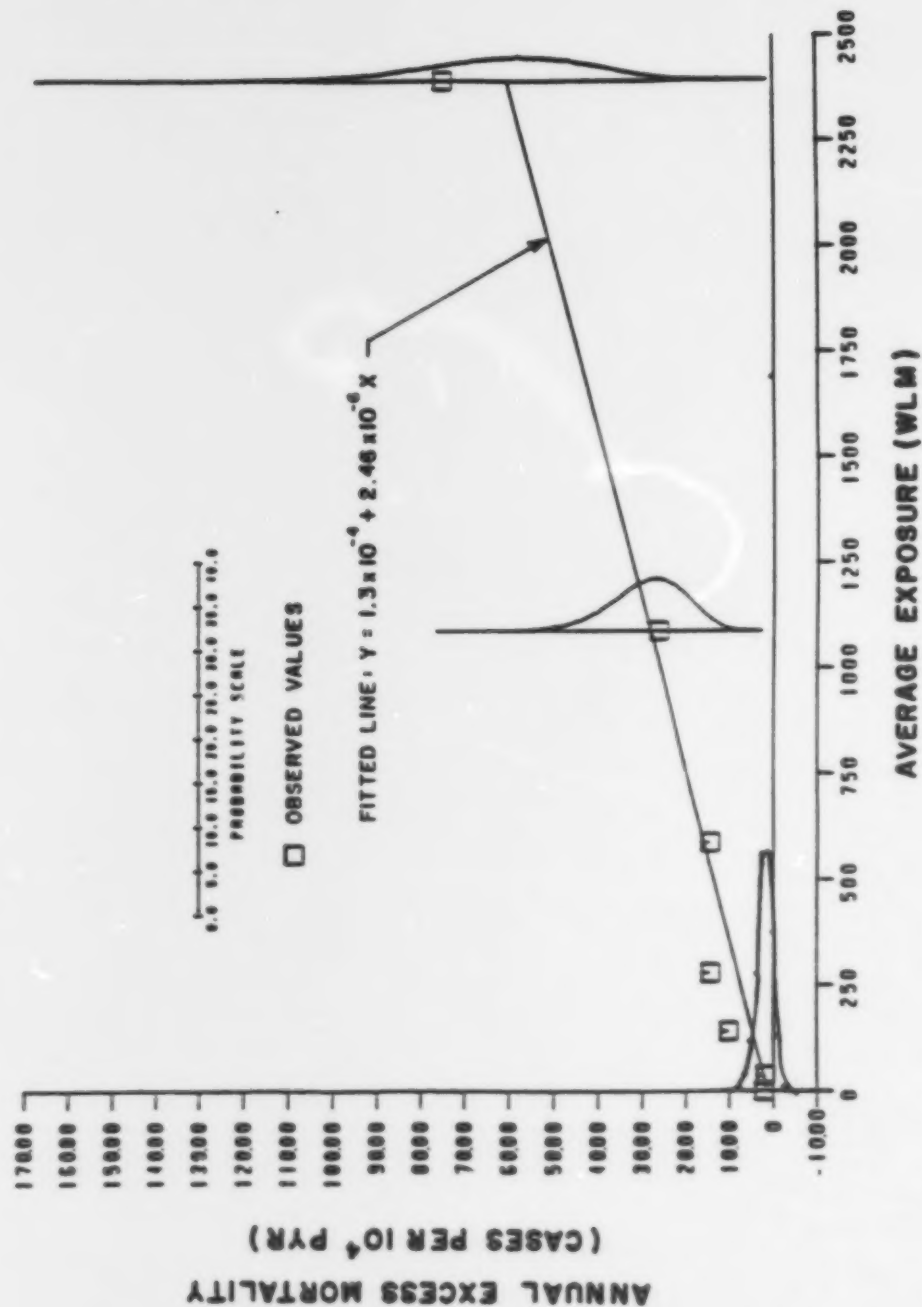


FIGURE 4.19b

MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)

ABSOLUTE RISK MODEL, ELDORADO URANIUM MINERS, PORT RADIUM

(SEE TABLE 4.9)

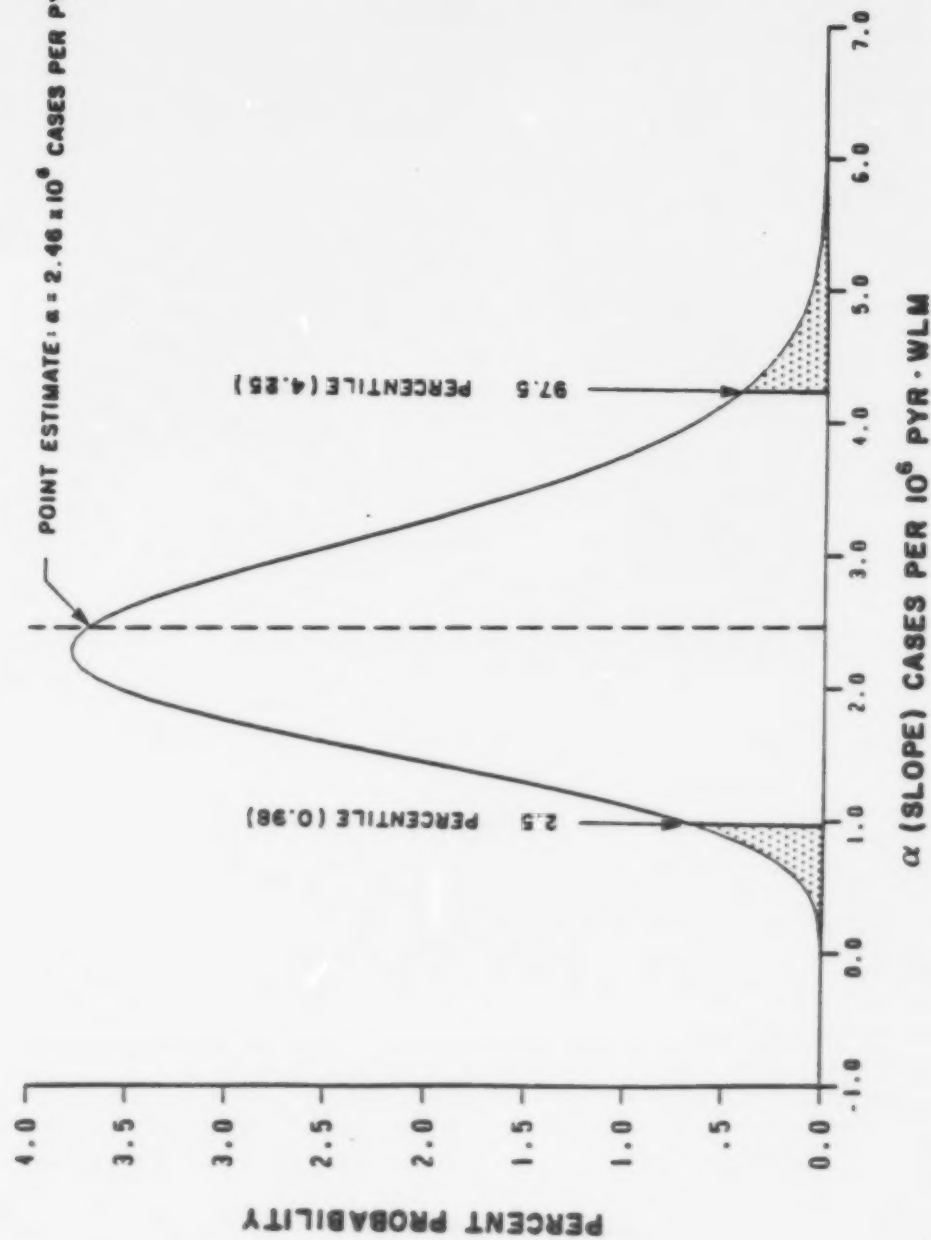


FIGURE 4.20d
INCIDENCE OF LUNG CANCER FOR ELDORADO URANIUM MINERS, PORT RADIUM
RELATIVE RISK MODEL
(SEE TABLE 4.9)

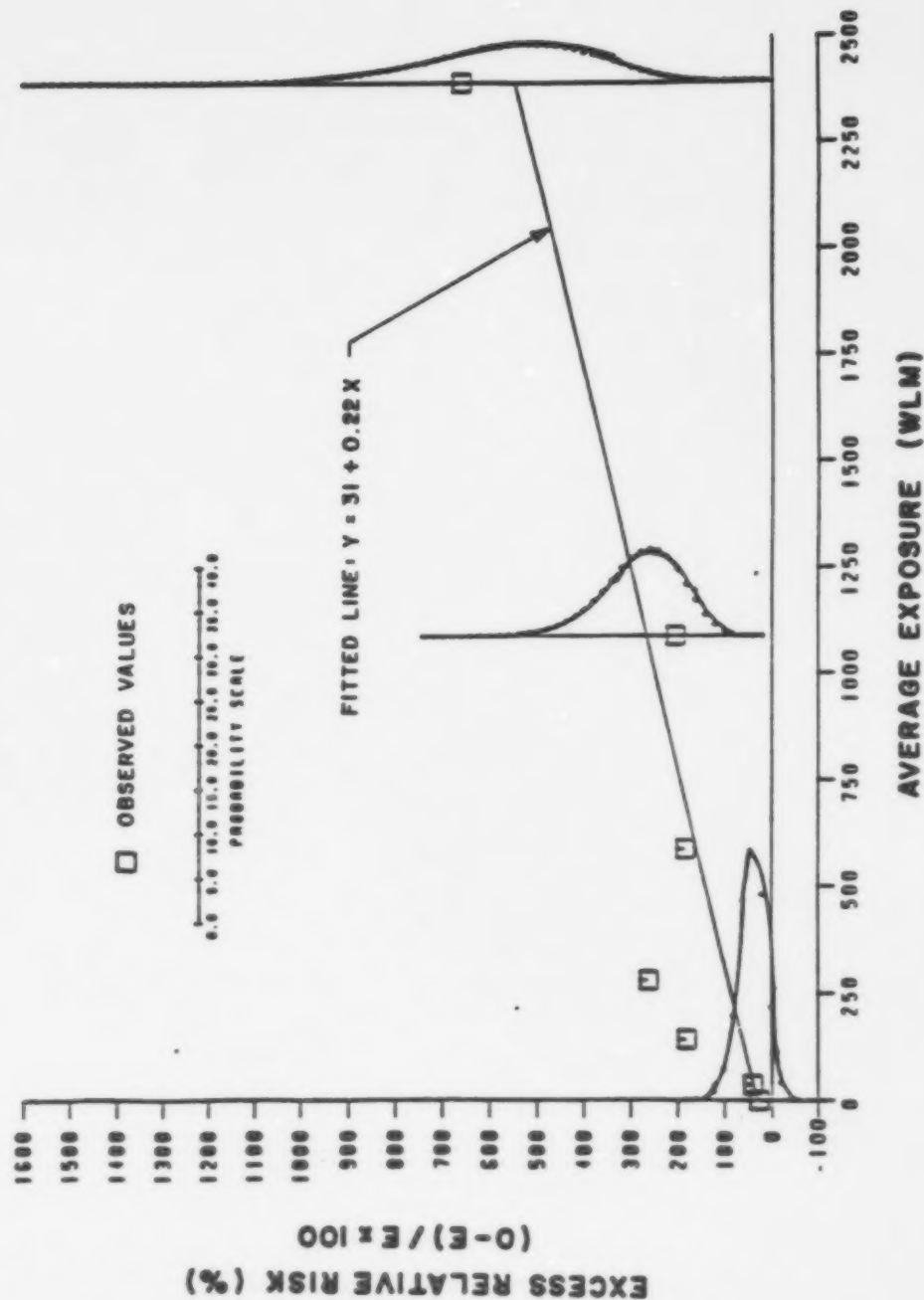


FIGURE 4.20b

MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)

RELATIVE RISK MODEL, ELDORADO URANIUM MINERS, PORT RADIUM

(SEE TABLE 4.9)

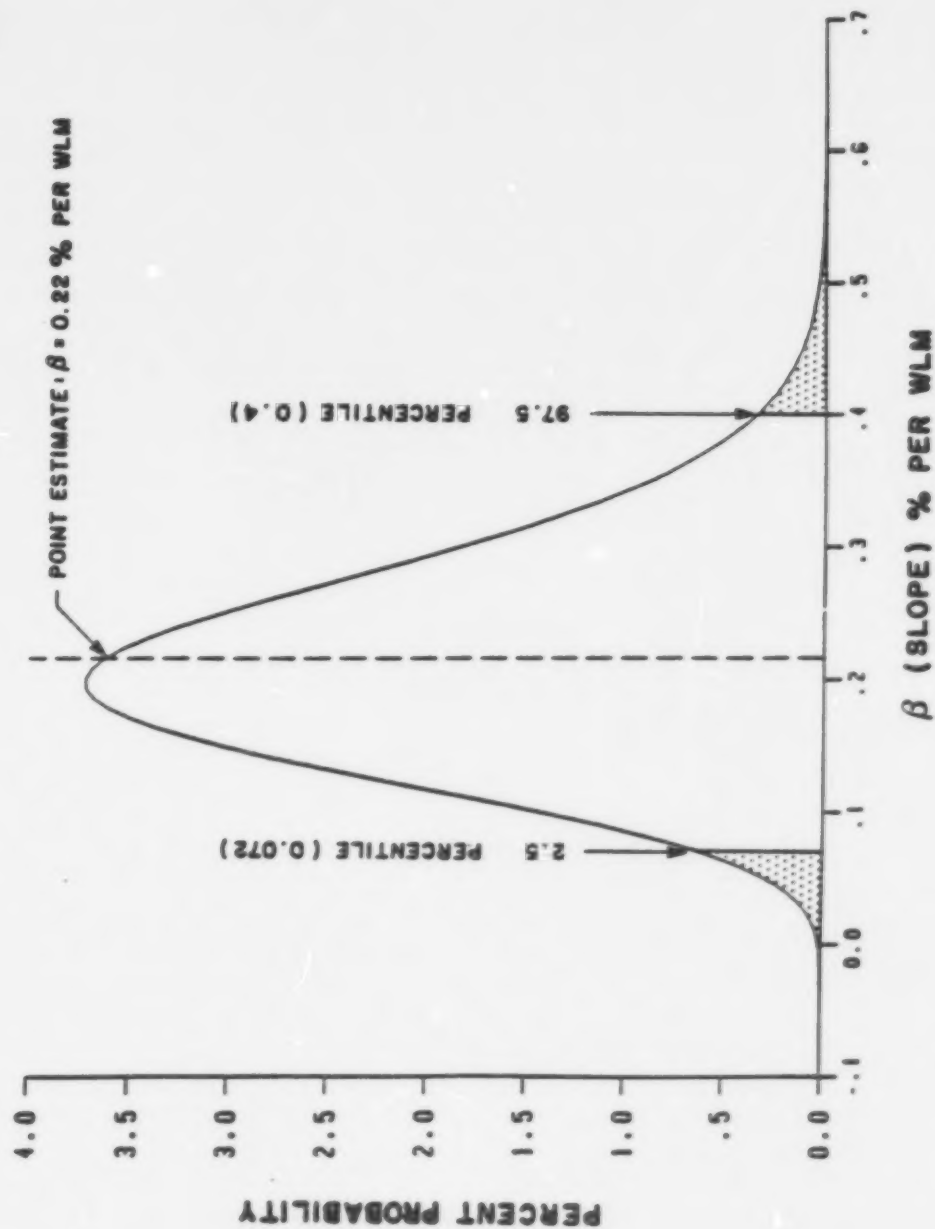


FIGURE 4.21a
INCIDENCE OF LUNG CANCER FOR NEWFOUNDLAND FLUORSPAR MINERS
ABSOLUTE RISK MODEL
(SEE TABLE 4.10)

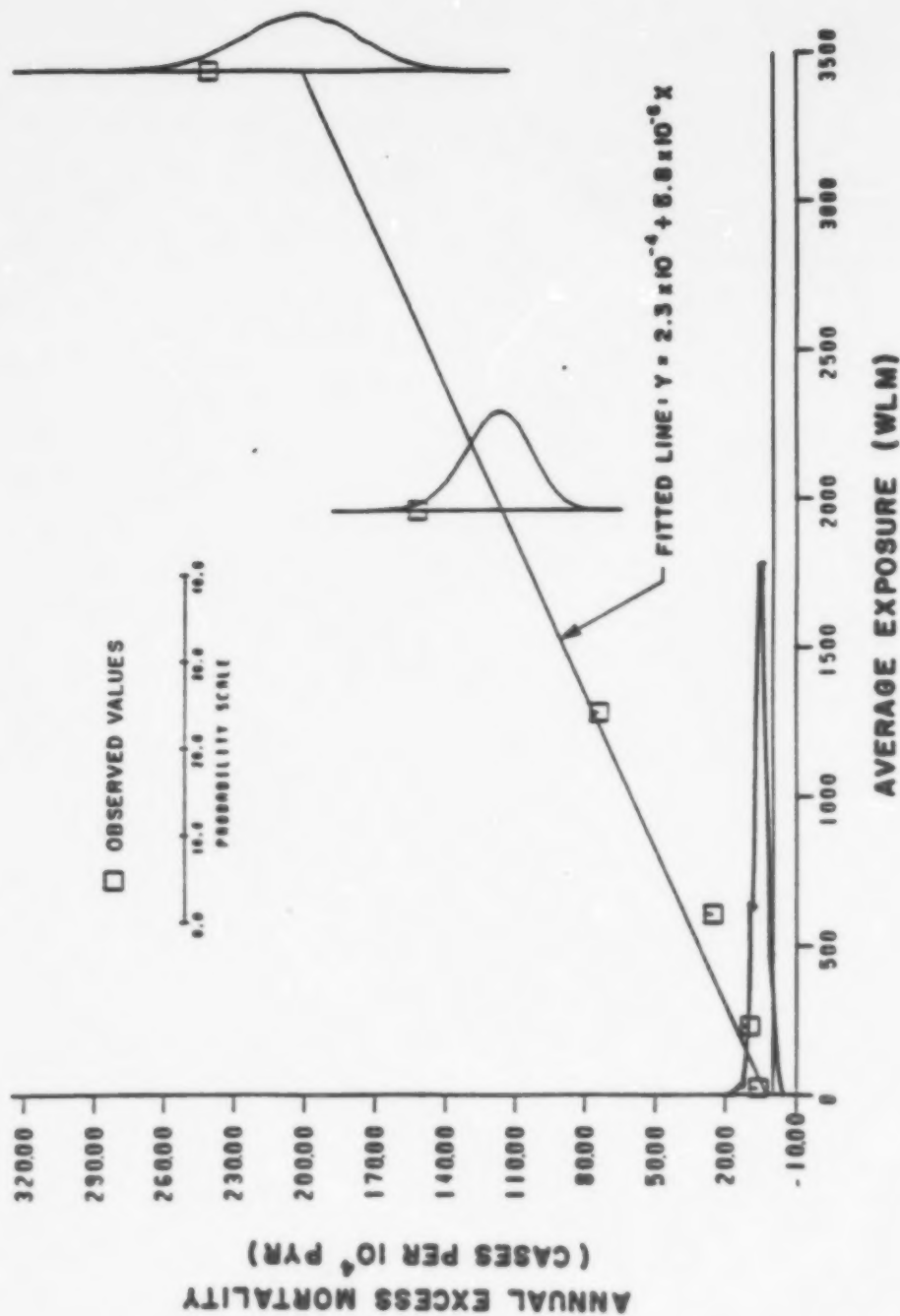


FIGURE 4.21b
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)
 ABSOLUTE RISK MODEL, NEWFOUNDLAND FLUORSPAR MINERS
 (SEE TABLE 4.10)

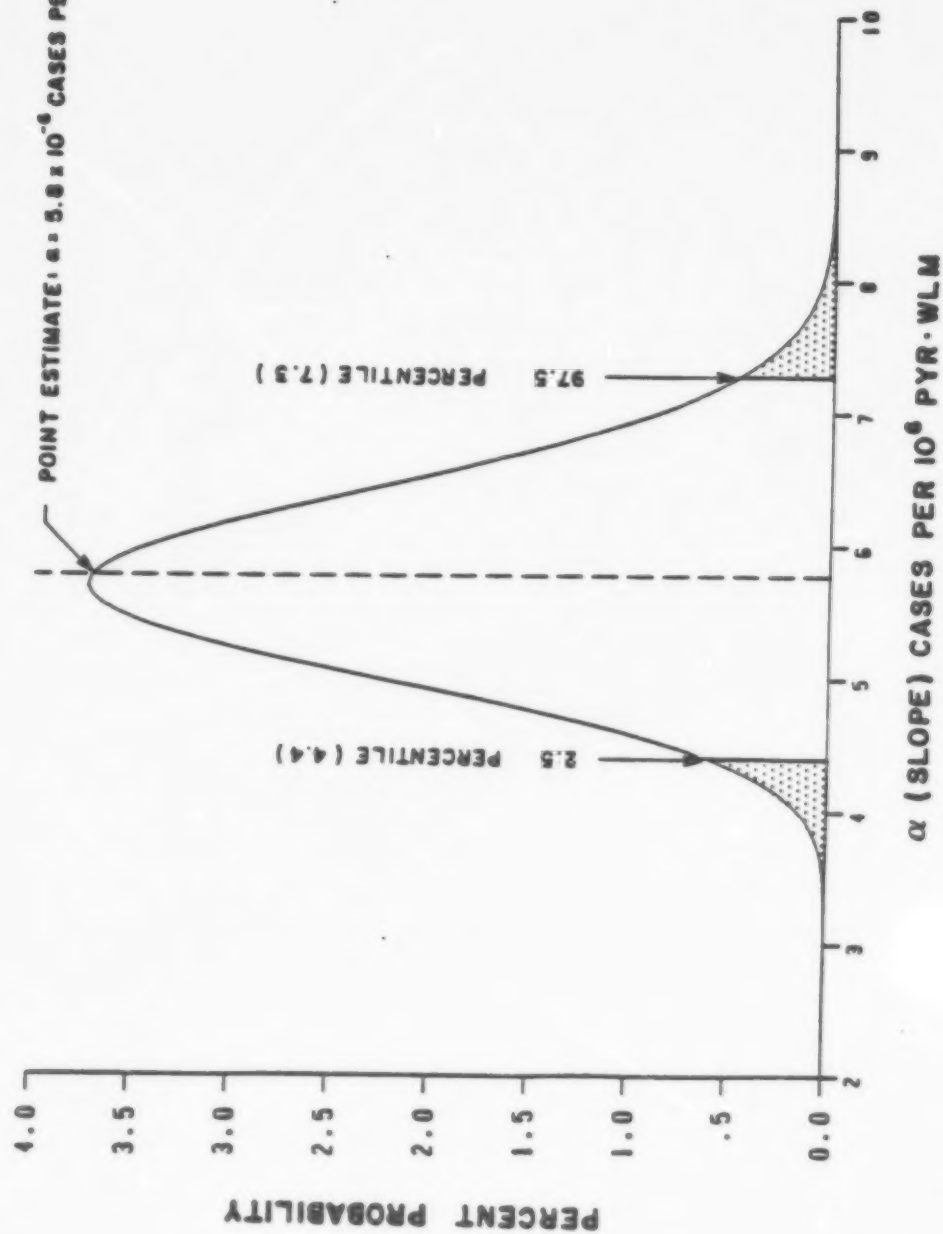


FIGURE 4.22a
INCIDENCE OF LUNG CANCER FOR NEWFOUNDLAND FLUORSPAR MINERS
RELATIVE RISK MODEL
(SEE TABLE 4.10)

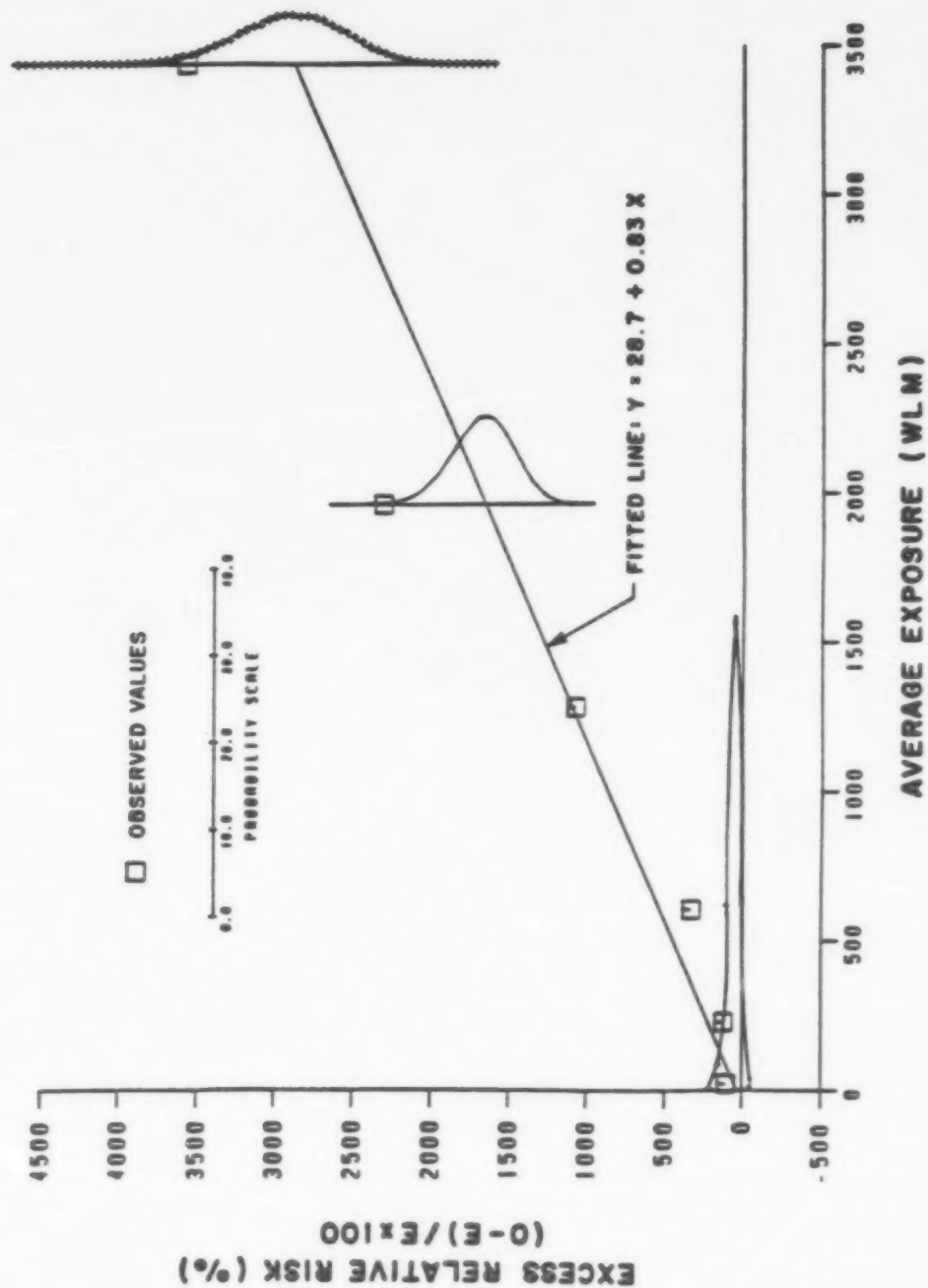


FIGURE 4.22b

MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)

RELATIVE RISK MODEL, NEWFOUNDLAND FLUORSPAR MINERS

(SEE TABLE 4.10)

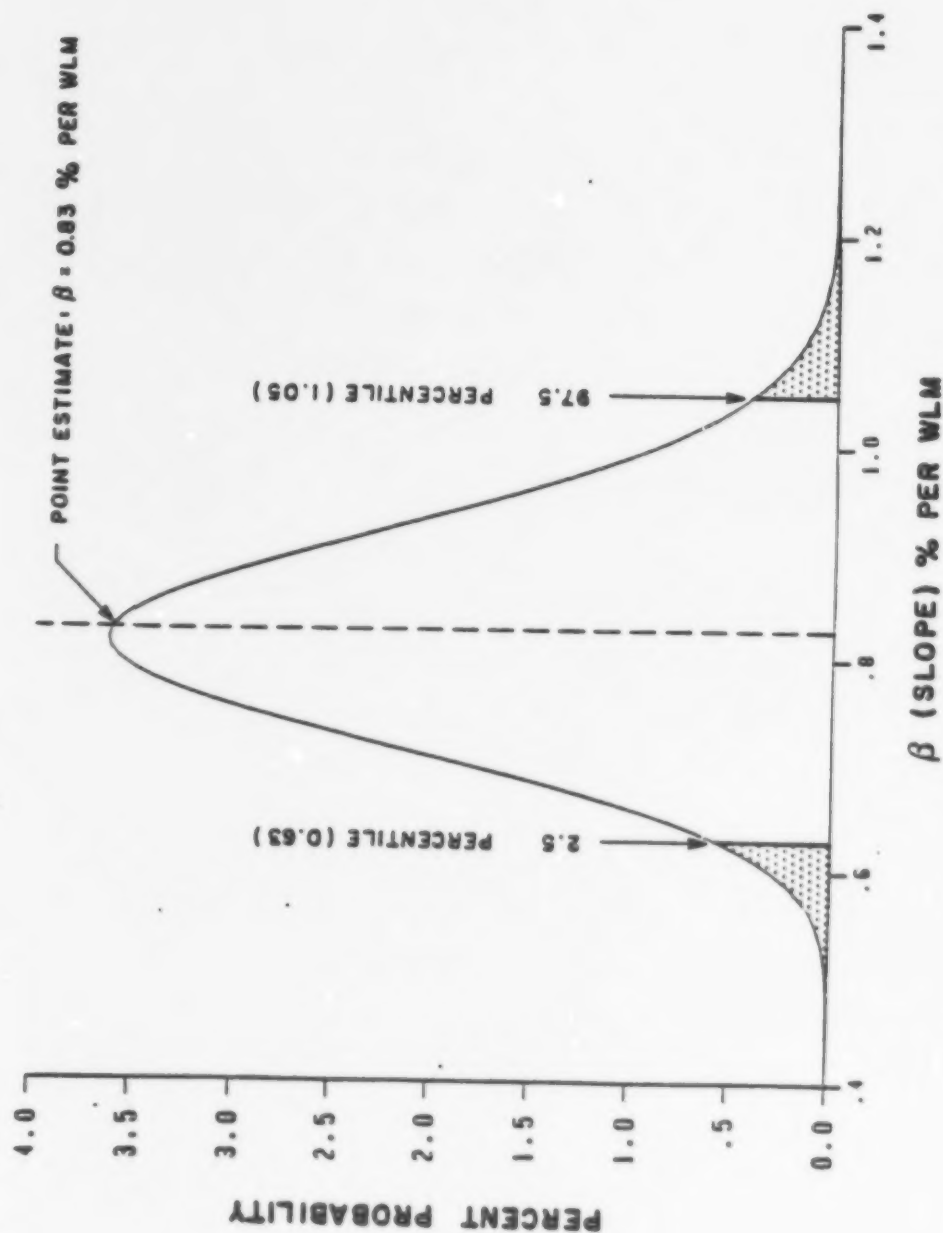


FIGURE 4.23a
INCIDENCE OF LUNG CANCER FOR SWEDISH IRON MINERS
ABSOLUTE RISK MODEL
(SEE TABLE 4.II)

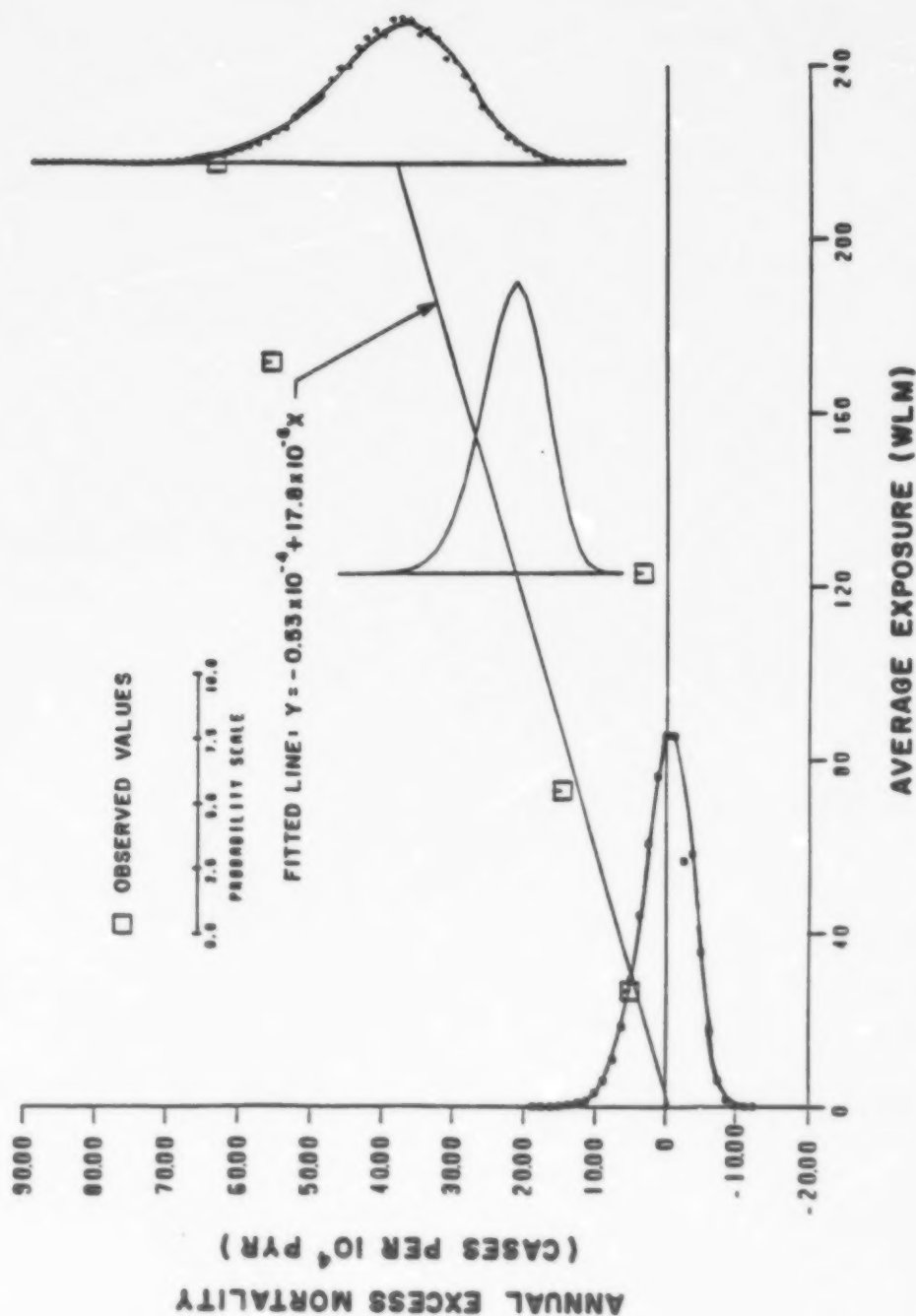


FIGURE 4.23b
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)
 ABSOLUTE RISK MODEL, SWEDISH IRON MINERS
 (SEE TABLE 4.II)

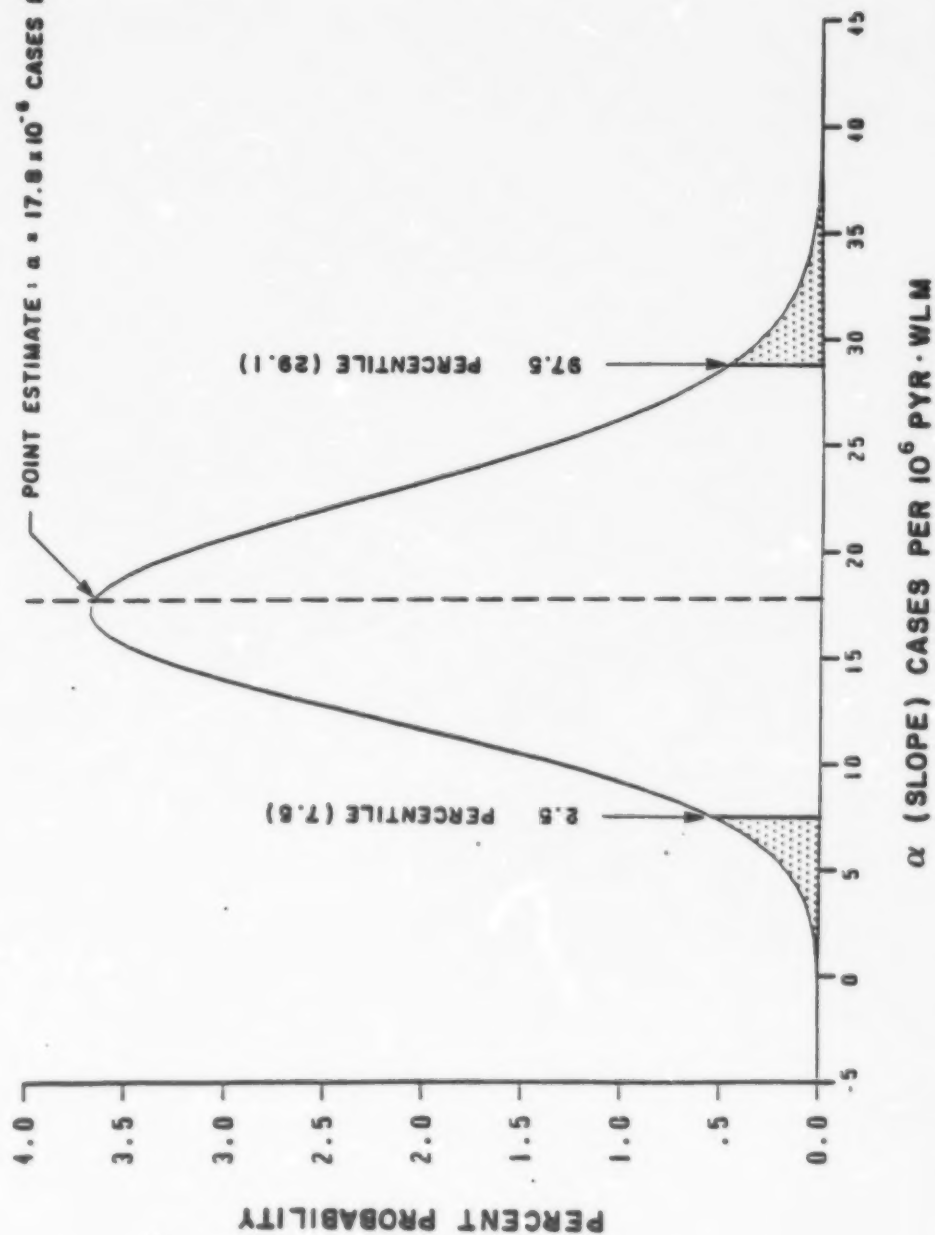


FIGURE 4.24a
INCIDENCE OF LUNG CANCER FOR SWEDISH IRON MINERS
RELATIVE RISK MODEL
(SEE TABLE 4.11)

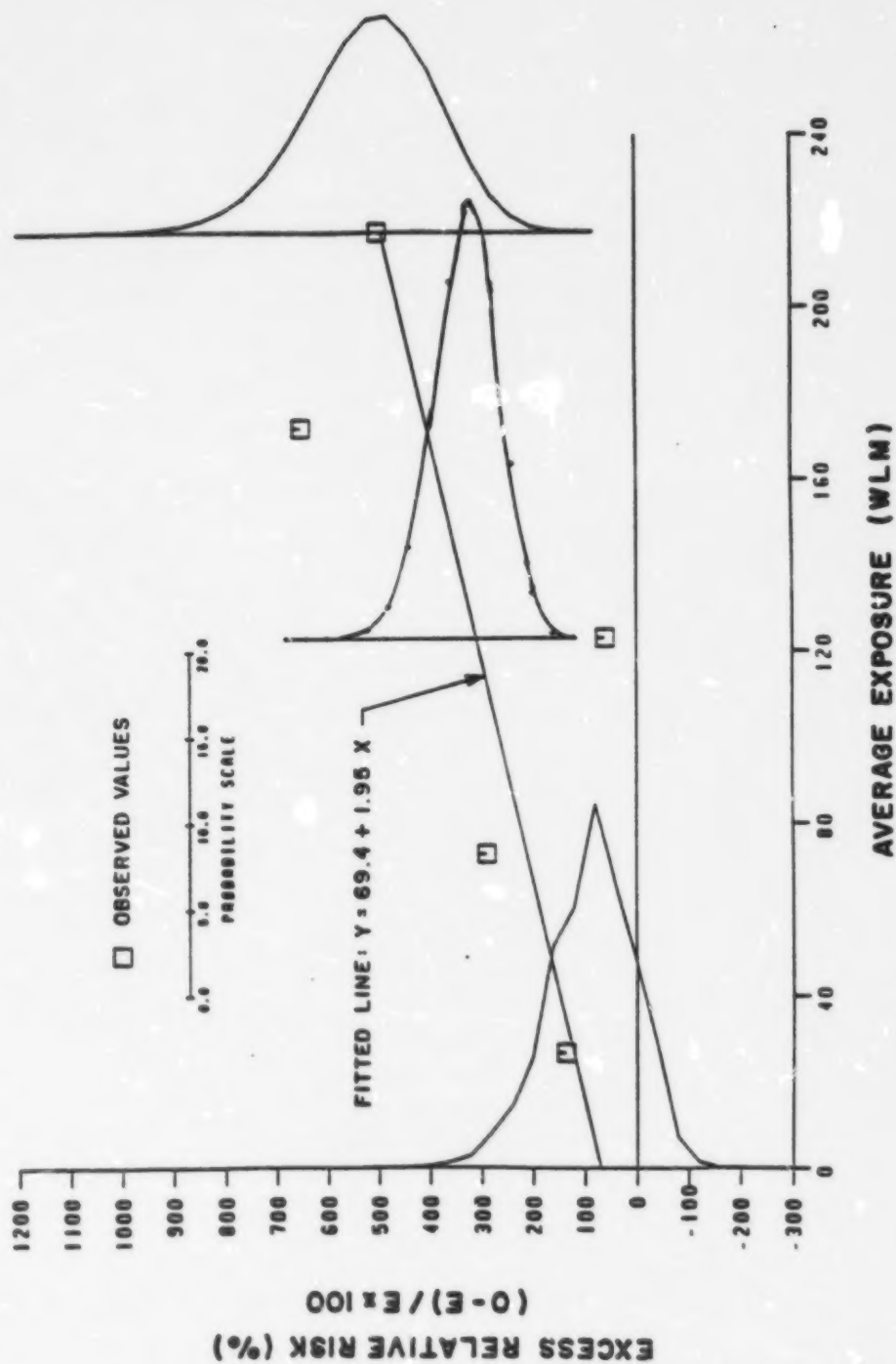
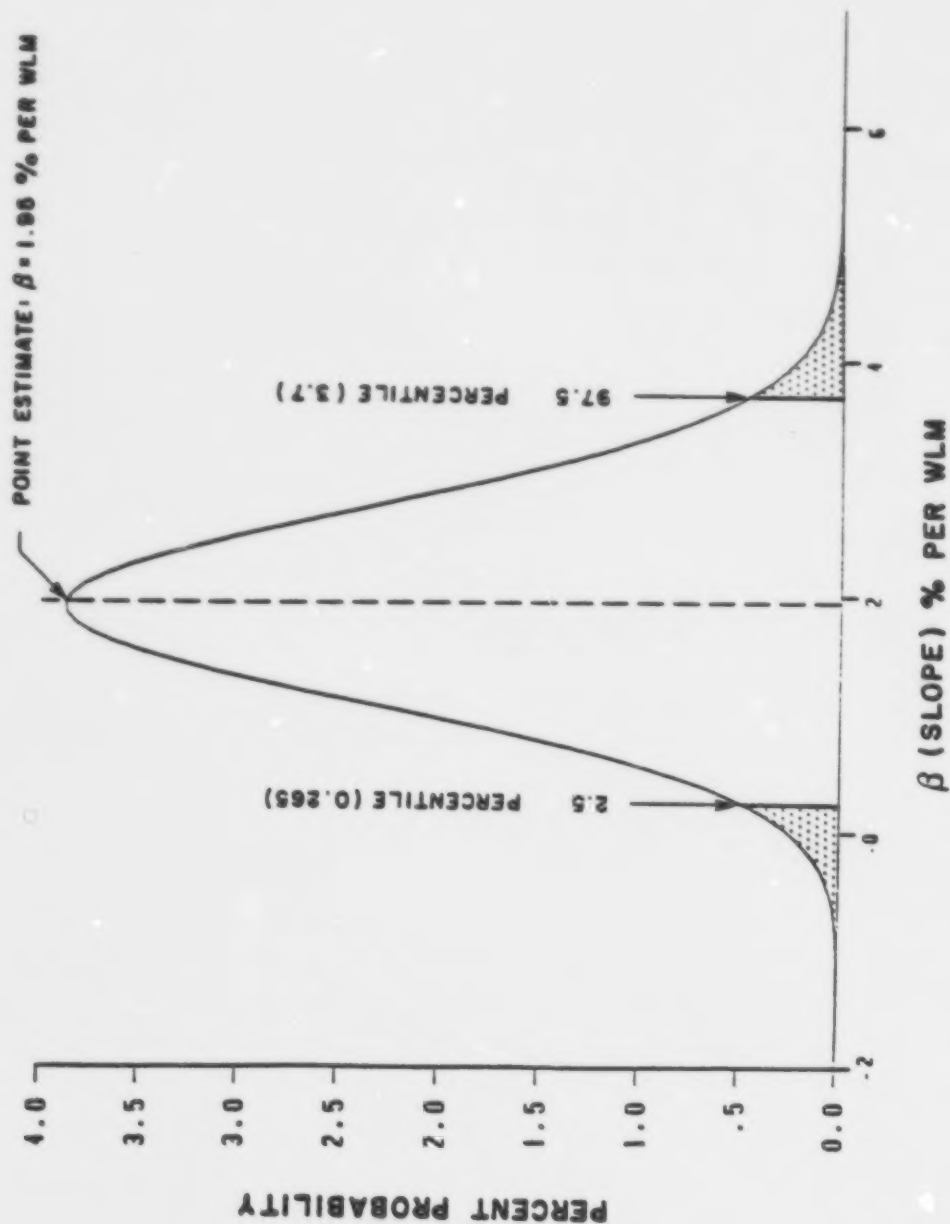


FIGURE 4.24b
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)
 RELATIVE RISK MODEL, SWEDISH IRON MINERS
 (SEE TABLE 4.II)



5.0 DISCUSSION

Management of the potential risk associated with exposure to radon and radon daughters is a key societal issue in many countries. The epidemiology of miners who were exposed to elevated radon daughter levels in the past form the principal basis for assessing the risk from exposure to radon and its daughters. Several of these studies have been reviewed in this report.

Studies Considered

In all of the studies, the miners' estimated exposures are uncertain, the exposures becoming more uncertain as we move backward in time, For reasons given previously in this report, the studies of U.S. miners, Ontario miners, and Czechoslovakian miners currently provide the strongest basis for risk estimation.

The strengths of these groups are that they are all large, well-traced cohorts for which there is considerable information for period of interest on which to base risk estimates. To the best of our knowledge there is no systematic bias with regard to the magnitude of the exposures estimated in these studies. It should be acknowledged, however, that the uncertainties for exposures of individual miners could be very large, particularly the exposures associated with the early years of mining. Of these three groups, the U.S. miners were exposed to the highest radon daughter concentrations, Czechoslovakian miners were exposed to intermediate levels and Ontario miners were exposed at the lowest levels. To the present time, the effect of smoking in either the Ontario miners or Czech miners has not been accounted for. The smoking experience of the U.S. miner cohort is relatively complete compared to other groups of miners and some analyses which correct for smoking have been performed (e.g. Whittemore McMillan, 1983).

The Eldorado Beaverlodge miners are reported to have been exposed to relatively low WLM exposures and the results of this study are potentially very useful. At the present time however, for the reasons given earlier, the exposure estimates currently assigned to the Beaverlodge cohort are believed not only to be uncertain but also to have been significantly underestimated, at least for the pre-1960 exposure interval. Overall, the exposures may have been underestimated by a factor of 2 to 3.

Exposures in the Port Radium miner study are clearly highly uncertain. Moreover, as noted by the investigators themselves, exposures are likely to have been underestimated and therefore risk estimates derived from this study should be used with some caution.

The remaining two study groups investigated in this report include the Swedish iron ore miners and the Newfoundland fluorspar miners. Both of these cohorts are relatively small and all of the exposure estimates had to be performed via extrapolation backwards in time. Therefore, the exposure estimates are likely to be highly uncertain. In the case of the Newfoundland miners, efforts were made by simulation and mathematical modelling to take account of the effect of the changing in ventilation conditions with time. Current estimates of exposures in this group are unlikely to be improved by additional study. This is different from the study of the Swedish Malmberget iron miners in which investigators assumed that the conditions which existed in the 1968-1972 period when the first radon measurements were made in the Malmberget mines, were comparable to those which existed in earlier periods (as early as 1930). This is unlikely, as improving ventilation will likely reduce both the radon levels and the equilibrium factor. Therefore in our view, risk estimates derived from the Malmberget study are likely to be underestimated somewhat, perhaps by a factor of about 2.

Early Exposure, Other Hard Rock Mining (OHR) and Smoking

From the discussion in Chapter 2 and the results of the regression analyses on the Ontario miners in Chapter 4, it is clear that OHR mining experience, irrespective of radon daughter exposure, can influence the risk analysis. It seems therefore desirable to examine the study groups on the basis of exposure histories subdivided according to whether or not the men had experience in only uranium mines or in uranium mines plus OHR mines. This is indeed quite feasible for the U.S. miners. Analyses have already been done for the Ontario miners with follow-up to the end of 1981 for uranium miners with no prior gold experience (some of these miners may have had experience in OHR mines other than gold however). Similarly, study group A of the Czech miners appears to have had a relatively pure uranium mining experience. Control of the study groups in this fashion would help to eliminate some of the confounding associated with imperfectly known work histories.

It is also worthwhile to examine the effect of pre-1950 versus post-1950 exposures in the U.S. mining cohort. For exposures prior to 1950, it was necessary for the investigators to rely totally on extrapolation, the knowledge of the mining conditions, the ventilation parameters and the mines for exposure reconstruction. Therefore, while we are not aware of bias in these exposure estimations, the exposures, especially for individual miners, are likely to be highly uncertain and indeed relatively more uncertain than exposures derived on the basis of more recent data.

Consider Figure 5.1 which shows posterior distributions of the risk coefficient (in units of cases per million person-WLM) for U.S. miners with and without pre-1950 exposure. Part A) of Figure 5.1 shows some 91 lung cancer cases in men who started

exposure prior to 1950, based on follow up through to 31 December 1982. Arbitrarily assuming that the overall exposure of this group of miners could be uncertain by $\pm 50\%$, it was estimated that the cumulative WLM of this entire group of 91 miners would likely be in the range of from 5.8×10^5 to 1.6×10^6 WLM. Using these data in the cumulative WLM Bayesian model (see section 4.2.1 and/or Appendix I), the (posterior) probability density function shown on Figure 5.1A was calculated. Based on these data, the likely range of the risk coefficient (with follow-up to 31 December, 1982) would be from perhaps 50 to 200 cases per million person-WLM, with a mean value of approximately 80 cases per million person-WLM.

Similarly, if we consider the 168 miners with lung cancer who have no pre-1950 exposure, the cumulative exposure for the group is calculated to be in the range 1.3×10^6 to 2.4×10^6 WLM. Applying the cumulative WLM model to the data, we calculate (see Figure 5.1B) that the likely range of the risk coefficient (for miners starting exposure after 1950 with follow-up to 31 December, 1982) to be in the range of perhaps 60 to 150 cases per million person-WLM with a mean value of about 86 cases per million person-WLM. It is interesting to note that while the average risk factor doesn't appear to change significantly, uncertainty about the mean value is smaller. It should be noted that these exposure estimates were calculated for uranium mining exposure only, exclusive of OHR mining exposures. The effect of including OHR exposure into the risk estimates would be to reduce (in inverse proportion to the added WLM) the estimated risk coefficient.

Consider also the effect of smoking which is illustrated in Figure 5.2. As of 31 December 1982 there were 20 miners whom the U.S. NIOSH data base assigns to the never-smoker category. For this group of men, the cumulative exposures calculated in the

same fashion as before are estimated to be in the range of 3.8×10^5 to 6.5×10^6 WLM. Applying the cumulative WLM approach (Appendix I), a mean risk of about 37 cases per million person-WLM is estimated, with a range of from perhaps 20 to 90 cases per million person-WLM. This can be compared to Part B of Figure 5.2, the posterior distribution of risk coefficient for all U.S. miners, (with follow-up to 31 December, 1982 and including nonsmokers). Here, there are 259 lung cancer cases whose cumulative WLM is estimated to range from about 1.9×10^6 to 4×10^6 WLM. The mean risk value increases by roughly a factor of 2 from the never-smokers (which are included in this group) to about 81 cases per million person-WLM. The uncertainty range about the risk value is shifted and extended, now ranging from approximately 50 to 160 cases per million person-WLM. These rather simple analyses suggest that risk coefficients calculated on the basis of the U.S. group as a whole (which includes never smokers, former smokers and smokers) are perhaps two times too large for nonsmoking miners. The role of smoking in the causation of lung cancer in miners clearly merits further consideration.

Absolute and Relative Risk Factors

Finally, consider Figures 5.3 and 5.4. These figures summarize the risk factors calculated in this report using EVM analyses and the corresponding 95% probability intervals, for the absolute risk model and the relative risk model, respectively. Both the absolute and relative risks calculated in this report were calculated for a "constant" risk model and can be interpreted as a kind of average over the exposure history and period of follow-up for each of the cohorts studied.

In our view, the U.S., Ontario and Czechoslovakian groups currently provide the strongest studies on which to base risk

estimates. Based on analysis of these groups, a reasonable range of risk coefficients are shown on the Figures. The absolute risk coefficient is estimated to range from <5 cases per million person-years per WLM to perhaps 15 cases per million person-years per WLM. For the relative risk model, the range is from <0.5% per WLM to perhaps 1.5% per WLM. A recently reported study of lung cancer risk in New Mexico uranium miners estimates an excess relative risk of 1.1% per WLM (Samet et al., 1989, p. 419), a value consistent with those calculated in the present study.

FIGURE 9.1
POSTERIOR DISTRIBUTION OF RISK COEFFICIENT
FOR U.S. MINERS WITH AND WITHOUT PRE-1950 EXPOSURE

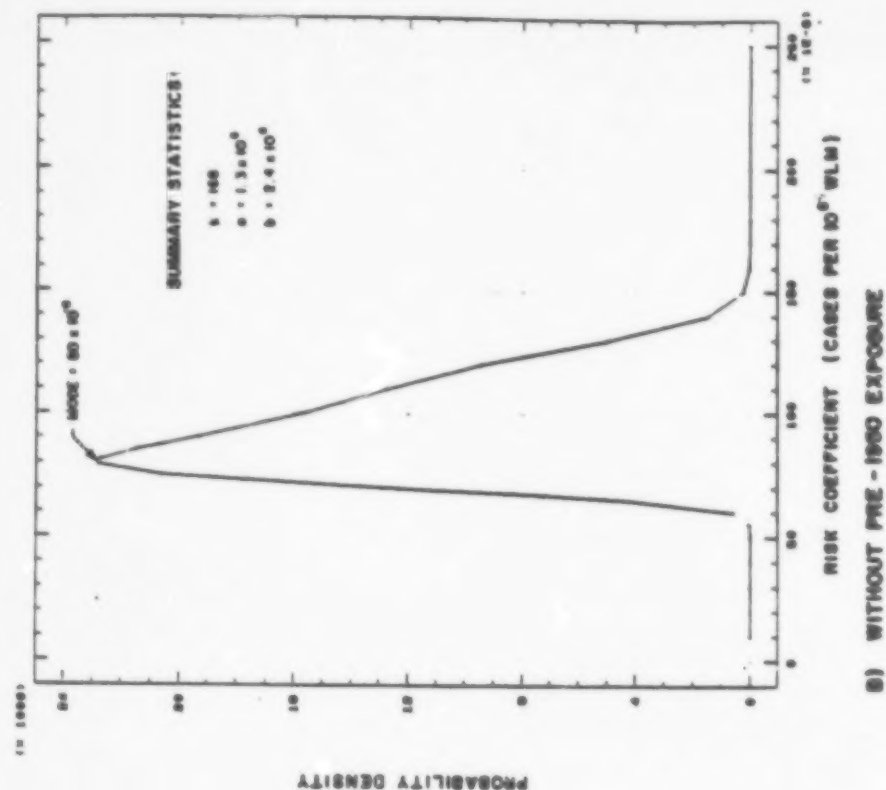
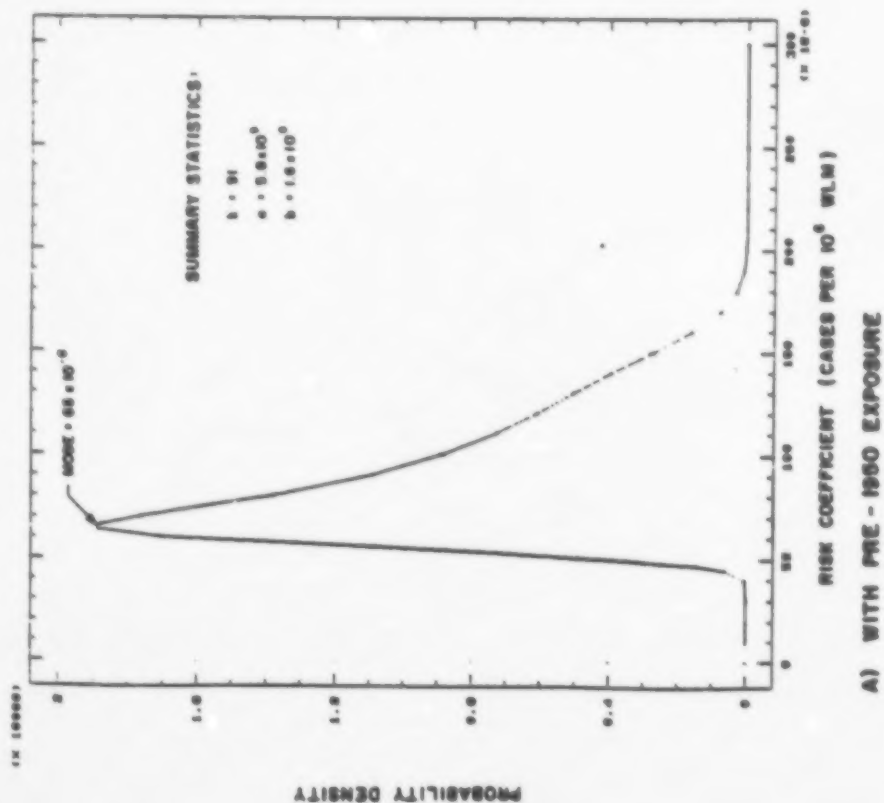


FIGURE 8.2
POSTERIOR DISTRIBUTION OF RISK COEFFICIENT
FOR NON-SMOKING AND ALL U.S. MINERS

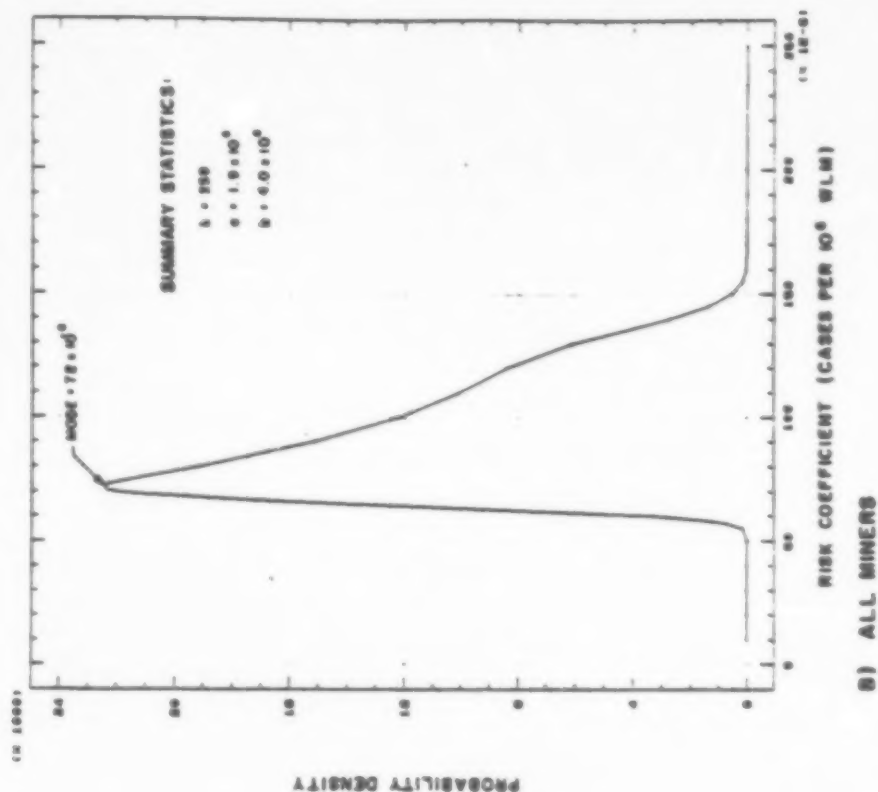
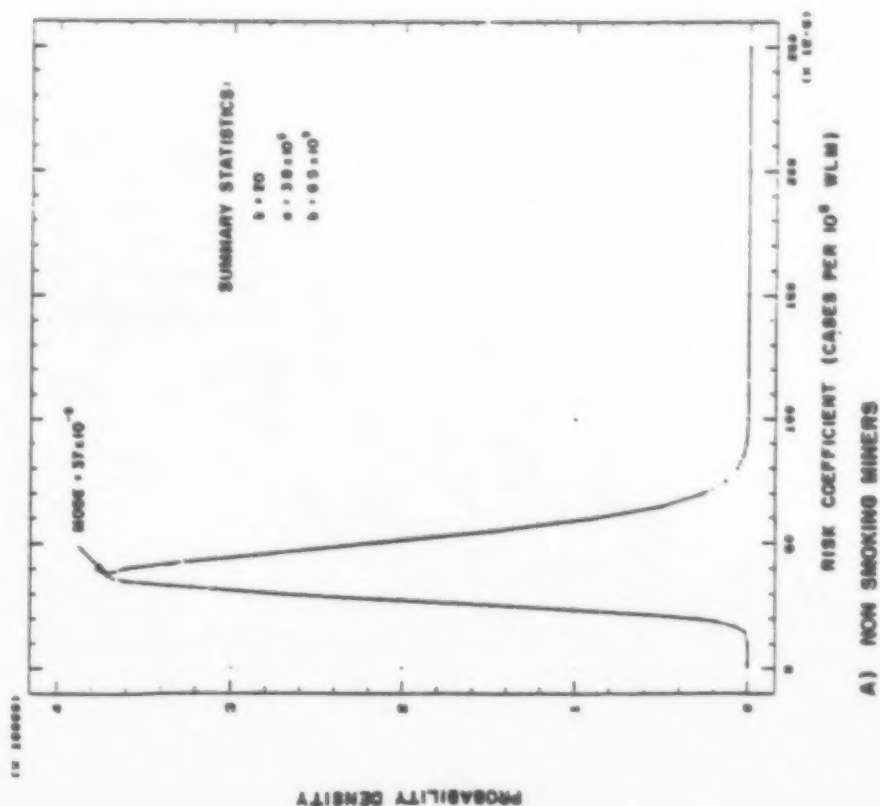


FIGURE 5.3
SUMMARY OF RISK FACTORS
FOR ABSOLUTE RISK MODEL

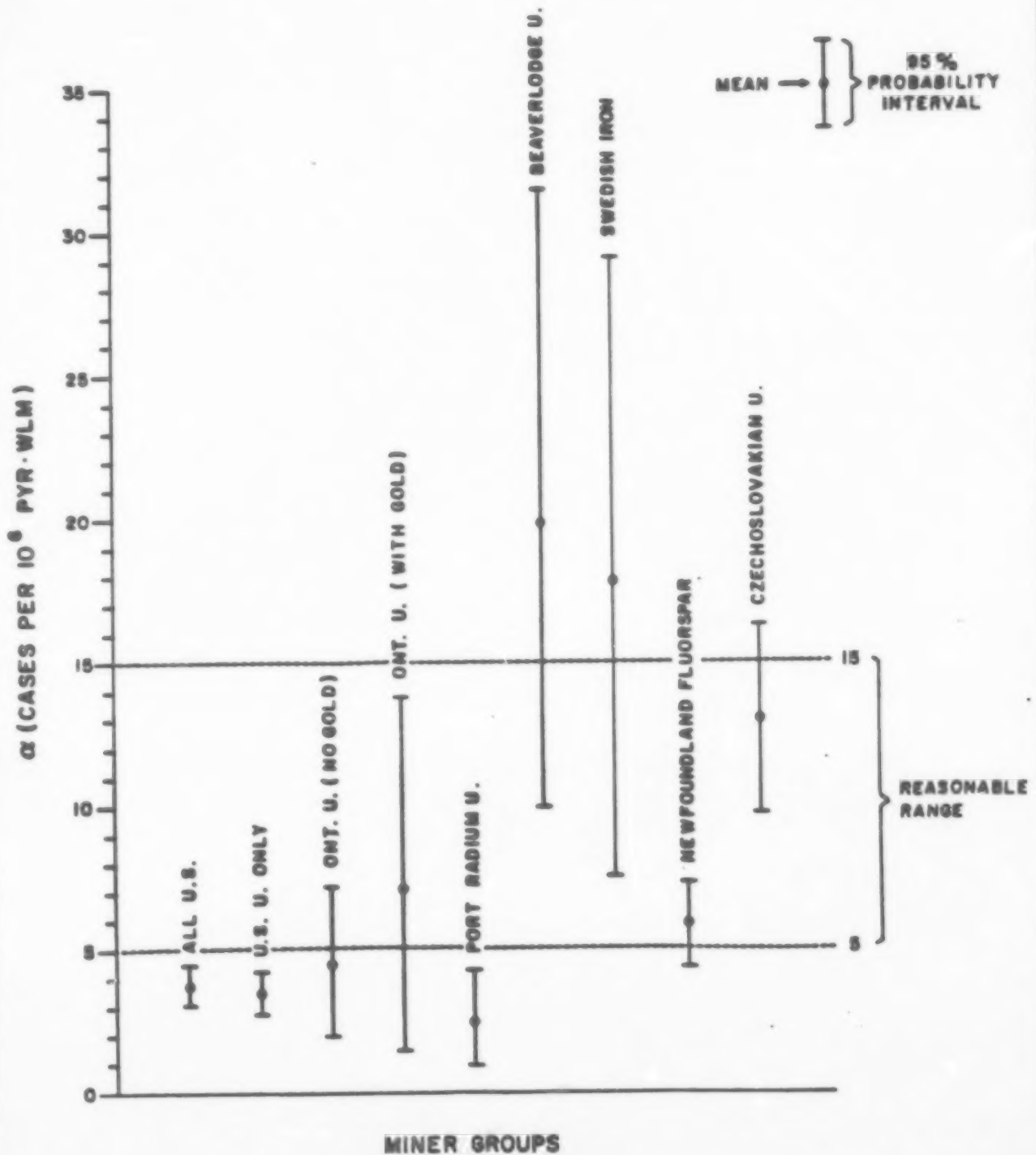
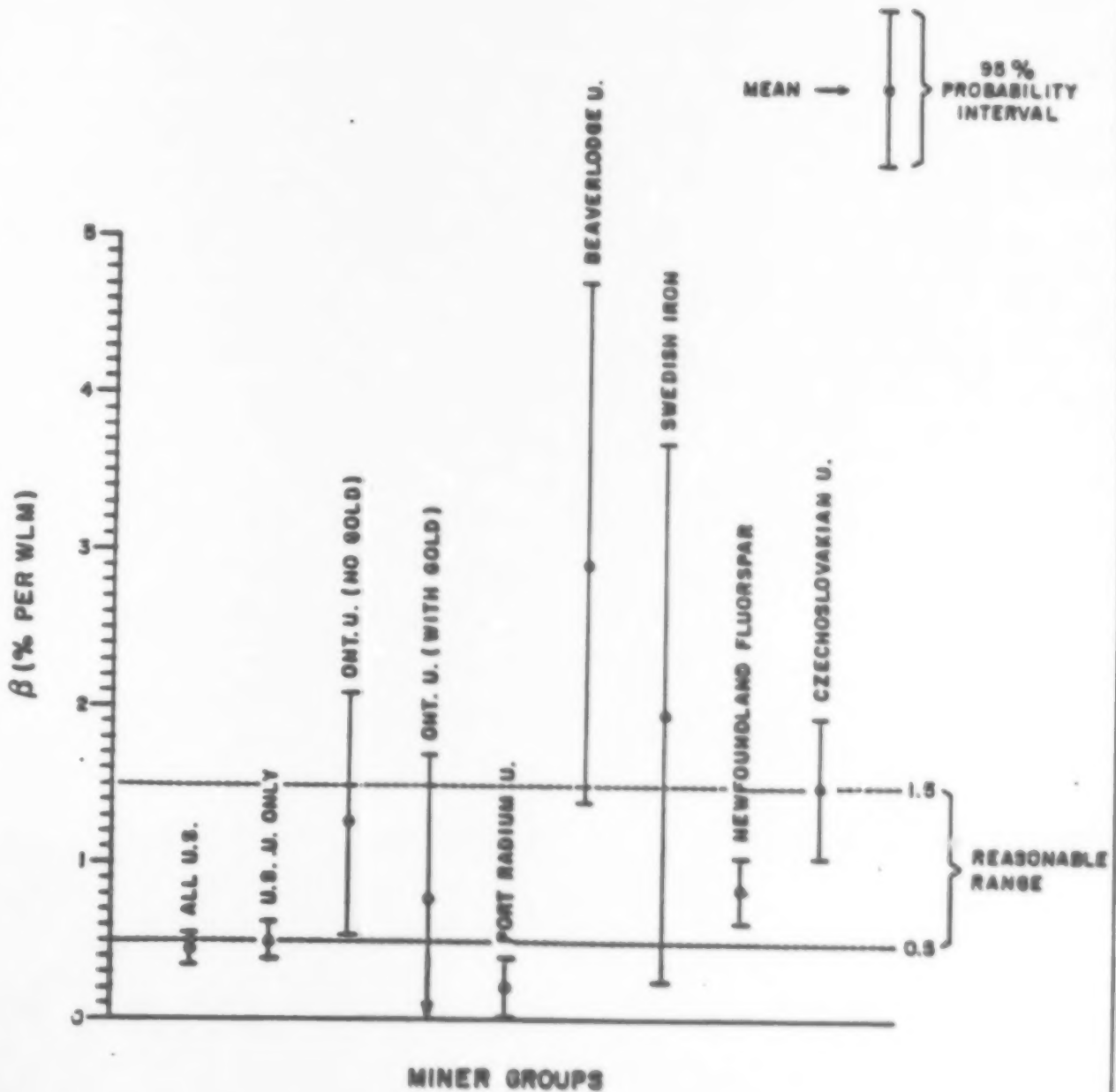


FIGURE 5.4

SUMMARY OF RISK FACTORS FOR RELATIVE RISK MODEL



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MINER STUDY APPENDICES

- A. U.S. MINER STUDY
- B. ONTARIO URANIUM MINERS
- C. CZECHOSLOVAKIAN MINERS
- D. BEAVERLODGE MINER STUDY
- E. PORT RADIUM MINER STUDY
- F. FLUORSPAR MINERS
- G. SWEDISH IRON ORE MINERS



APPENDIX A: U.S. MINER STUDY

Considerable effort has been applied to the study of radiation exposures and lung cancer in underground miners in the western United States. As discussed in the main body of this report, various investigators have examined not only uranium mining experience, but also given consideration to previous underground hard rock mining experience in non-uranium mines. This has already been noted as being a potentially important factor.

This appendix provides some additional information and an extensive Bibliography to assist interested readers. Principal attention is given to studies of Colorado Plateau miners; however, in view of the relatively recent and increasing interest in studies of New Mexico miners, a few comments and bibliographic citations relevant to this group are also provided.

A.1 History

The discovery of radioactive ores in the Colorado Plateau dates to between 1881 and 1887. The ores contained vanadium, uranium and a small quantity of radium (Holaday et al., 1964). Prior to demand for uranium and radium, vanadium was mined on a small scale. Radium production became more important through the period of 1916-1923. However, U.S. radium production eventually lost its competitiveness due to radium from high grade Belgian-Congo ores and during the period from 1930-1945, the vanadium content of these western ores was the principal objective of mining. Subsequently, through the defense initiatives associated with the World War II, attention turned more towards uranium (Lundin et al., 1971).

The uranium mining industry had expanded somewhat by 1949 and by 1950 some 500 men were engaged in mining of uranium ores in the

Colorado Plateau area, mostly in small underground workings with an average production of about 1 ton/man-day (Holaday, 1967). According to Holaday, the employment peak was reached in 1960 when about 5,800 underground miners were employed. By 1967, this had declined to approximately 2,800 miners who were then working and producing approximately 3 tons/man-day. Holaday also notes that by 1967 the occupational health field station had on file environmental data on over 1,200 different mining operations. However, he also indicates that an unknown additional number of operations were never surveyed.

Clark Cooper (1962) writing in a special supplement of the *Journal of Occupational Medicine*, notes that in 1953 or 1954 large deposits of primary uranium ores had been discovered in the Moab, Utah area and in the Grants area of New Mexico. Cooper also notes that by that time the largest number of miners working in uranium were in the northwestern section of that state.

Cooper (1962) suggests that "the unhappy events in the Schneeberg/Joachimsthal mines in the Erz Mountains were reviewed in the American literature by Heuper in 1942 and by Lorenz in 1944. These reviews were fresh in the minds of people in responsible positions." (ibid, pg. 615) and that in 1949 concern for possible health hazards in uranium mining was officially brought to the attention of the Public Health Service by the State Health Departments, the Colorado Bureau of Mines and several uranium producers who requested a study.

Consequently, the U.S. Public Health Service, in cooperation with the Atomic Energy Commission and the State Health Departments of Colorado, Utah, Arizona and New Mexico began environmental studies in uranium mines. By 1950, medical studies had been initiated (Archer *et al.*, 1962). Uranium miners were examined in various years (see e.g Table 1 of Cooper, 1962). Beginning in

1954 physical examinations were performed every 3 years on all miners who could be reached and who agreed to take the examination. The initial study population upon consisted of all men examined in 1954. At that time, some 90% of Colorado Plateau miners were examined.

Referring to the Seven State Uranium Mining Conference on Health Hazards held in Salt Lake City, 22, 23 February 1955 (Archives Industrial Health, Vol. 12, 1955), Holaday notes that this meeting recommended that all states adopt a tentative working level of 10^{-10} Ci/L. For practical purposes, the recommended standard was equivalent to 1 WL or 12 WLM per year of exposures. Holaday indicates that this recommendation was adopted as a guide by official agencies in most uranium mining states.

Holaday (1969) also refers to the Governors' Conference in Denver (1960) at which time the experience of lung cancer in the miners was sufficient "to indicate that the experience of European miners was being repeated." As a result, efforts were instituted to reduce miners' exposures.

Starting in the early 1960s, excess lung cancer incidence became apparent among uranium miners, and by the end of 1958, the federal government took action and lowered the maximum permissible annual exposure from 12 WLM per year to 4 WLM per year.

Table 2 of Holaday (1969) documents improvements in radon daughters exposure of the Colorado Plateau mines. In 1961 only 21% of the mines studied had WL measurements below 1 WL, by 1967 70% of the mines fell in the less than 1 WL range.

Holaday and Doyle (1964) suggest that until shortly before 1964 the roads system serving the mines in the Colorado Plateau area

was inadequate, and that since most mines were located in remote areas, supplies of fresh water and electricity were often insufficient. Holaday and Doyle hypothesize that this lack of ready availability of electrical power may have contributed to early high radon daughter levels.

Holaday (1969) notes that in the early days of mining (i.e. early 1950s) the mines were typically shallow and were usually entered by a horizontal adit or incline and were almost always ventilated by natural draft only. Holaday indicates that in most of the mining operations, the miners would work in all areas of the mine, drilling, mucking or handling the ore or setting timbers, etc. Holaday notes that this pattern of working had been established when the mines were mined for vanadium. Most importantly, *"the atmospheric concentrations of radon/radon daughters might vary widely within the same mine, but it is probable that over a period of several months all the underground workers in one mine had similar exposures"* (ibid, pg. 549). Holaday notes that efforts were made to reduce the exposures of miners even before there was a precise method for measuring radon daughters.

Uranium was identified in ores in the Shiprock area of New Mexico around 1918. At that time, it received little attention. However, by 1950 there was more interest in uranium and various uranium outcroppings had been discovered in limestone and sandstone areas in the Grants mineral belt (Samet et al., 1981). The uranium rush followed in the 1950s and at various times during the period from 1950 through 1960, some 60 mines were in operation. Uranium market fluctuations starting in the early 1960s resulted in various expansions and shutdowns. Nonetheless, from 1966 through 1978, the annual output of uranium in the Grants area of New Mexico represented approximately 45% of the U.S. uranium production.

The New Mexico Health Department began monitoring radon daughter levels in New Mexico mines in the late 1950s with the aid of the state mine inspector's office. According to Samet et al. (1981), the maximum permissible concentration of radon daughters decreased from 25 WL to 10 WL in 1960; to 5 WL in 1963; to 3 WL in 1967; to 2 WL-1.75 WL in 1969; to 1.4 WL in 1973; and finally to 1 WL in 1976.

The Grants clinic, which opened in 1957 to service the miners, handles between 80-90% of miners pre-employment and follow-up examinations and keeps records of the movements of most miners in this area.

A recent paper by Samet et al. (1989) reports on the results of a case control study to investigate lung cancer risk in a cohort of the New Mexico underground uranium miners. With this exception, however, the majority of investigations of New Mexico miners to date have been examinations of morbidity and mortality amongst uranium miners and parallel investigations of miners exposures. The third annual report of the study by the University of New Mexico is particularly relevant with regard to exposure estimation, (Samet, 1985).

A.2 Measurements

Radon samples were taken from 1949 to 1950. Radon daughter measurements were taken starting in 1951. Originally, samples were taken by the Public Health Service and various other agencies for survey purposes. However, as a result of the seven state conference, many of the larger uranium companies initiated their own sampling programs in 1955. By 1956, the mining companies did most of the mine survey work while agencies continued their own control programs (Lundin et al., 1971). These measurements were carried out across the four states:

Colorado, Utah, Arizona and New Mexico.

As noted previously, for the entire period of 1951 through 1968, there were some 43,000 measurements of radon daughter concentrations available from approximately 2,500 uranium mining operations.

Holaday (1955) reports median radon levels in the order of 8,300 pCi/L for measurements made in the Colorado Plateau uranium mines. He notes that radon levels in European mines were estimated at approximately 1,000 pCi/L. This observation, coupled with measurements of high radon levels in some non-uranium mines (e.g. up to 2,100 pCi/L was measured in nonuranium mines in New York), encouraged Holaday to press for the examination of the then available data on the exposure of miners and their risk of lung cancer.

A.3 WLM Estimates

Wagoner et al. (1964) concluded that the excessive respiratory cancer rates amongst uranium miners was not attributed to age, smoking activity, heredity, urbanization, self-selection, diagnostic accuracy, prior hard rock mining or other ore constituents. They attributed the risk of response of respiratory cancer to airborne radiation. Miners who were examined in the Colorado Plateau area in the period 1951 through 1960 and for whom there were sufficient records made up the cohort. The average WL and underground duration in months were multiplied to arrive at average WLM for each classification of miners. Additional details were provided in a subsequent paper by Wagoner et al. (1965). The WLM calculation was performed for each miner, then categorized into groups according to exposure levels. At that time, approximately 12,000 radon daughter measurements were available for the approximately 1200 mines

under study. The WL used in the calculations were derived as follows:

"When there were multiple measurements in the mine during a calendar year an average annual exposure was calculated. Measurements from non-work areas were excluded from all calculations. When no measurements were available for a mine during a calendar year, estimates were made from the average of measurements for the same mine during the preceding and following calendar year or other mines on the basis of geographic proximity, similarity ore bodies, physical layout, ventilation and control efforts of regulatory agencies."
(Wagoner et al., 1965, p. 184)

More detailed measurements began in 1967 with the intention of presenting these data to the Federal Radiation Council (FRC) for their review so the FRC guidelines for the control of radiation hazards in uranium mining could be updated. The results of this update are presented in a paper by Lundin et al. (1969) which examined a cohort of 3,414 white and 761 nonwhite underground uranium miners who had taken physical examinations in 1950 through 1961. The results shown in Lundin et al. (1969) indicate that smoking uranium miners experienced an excess lung cancer risk ten times greater than nonsmoking miners. Also, according to Lundin et al. (1969), prior hard rock mining experience had little overall effect on lung cancer mortality but it was suspected to contribute more significantly to the lower exposure categories.

In 1971, Lundin et al. (Joint Monograph) reported on investigations of the cohort with the exposures updated from the start of mining through September 1969. The cohort of Lundin et al. (1971) contained 3,366 white and 780 nonwhite uranium miners

who had at least one month of underground mining prior to 1 January 1964. Radon daughter exposures in non-uranium hard rock mines were assumed to be 1 WL before 1935, 0.5 WL between 1935 and 1940, and 0.3 WL in 1940 and later.

As previously noted, radiation levels in uranium mines dropped sharply after 1967. This fact, combined with the drop out rate of the original cohort after 1960 of 10-50% per year, justified the assumption that only a relatively small additional exposure was contributed to this cohort from exposures received after September 1969.

Lundin et al. (1971) discuss their exposure estimation in various categories which implicitly have differing degrees of confidence, namely extrapolations, estimates and guesstimates. NIOSH (1985), based on the review of the U.S. PHS data, estimate the distribution of radon daughter exposure data by type of record as shown in Table A.1.

Many New Mexico miners are also included in the cohort study noted above. An independent epidemiological study of New Mexico uranium miners was initiated in 1977. This study has been performed by the University of New Mexico under the direction of Dr. Samet. The focus of Samet's study group is the retrospective analyses of a cohort of 3055 underground uranium miners with first underground experience before 1971. An outline of the approach to exposure estimation used in the New Mexico study is provided in the third progress report (Samet, 1985).

It is perhaps worth noting that New Mexico investigators found that the mean of the WL measurements provided the best indicator of the total mine exposure index which weights measurements by numbers of personnel exposed (Samet, 1985, pg. 2 and also Samet et al., 1989, pg. 416).

Table A.1

**RADON PROGENY EXPOSURE DATA SET FOR SURFACE* AND
UNDERGROUND URANIUM MINES IN THE UNITED STATES**

<u>Type of Record</u>	<u>Number of Records</u>	<u>Percentage of Total Data Set</u>
Guestimate	1,854	5.43
Estimate	23,159	67.88
Extrapolation	5,602	16.42
Measurements	3,505	10.27
Total Average Annual WL Records	34,120**	100.00

Notes:

* Adapted from NIOSH, 1985 (Table III-1).

** NIOSH (1985) indicate there were 32,662 annual average WL estimates for underground uranium mines, 1,458 for surface mines.

The terms "guestimates", "estimates", and "extrapolations" were defined by Lundin et al. (1971) as follows:

"Guestimates" were annual WL values assigned to mines operating before 1951. Guesimates were made on the basis of knowledge concerning ore bodies, ventilation practices, emanation rates from different types of ores, and on radon or radon daughter measurements made in 1951 and 1952.

"Estimates" were average WL's for an area based on actual measurements made in a locality, district or state.

"Extrapolations" were interpolations or projections of annual WL values based on actual measurements made in the same mine during earlier or later years.



A.3.2 Miners' Employment History

The employment history of U.S. miners is documented by various means. Miners were interviewed during physical exams about mining experiences. In addition, supplemental information from subsequent annual uranium miner censuses, records of official agencies and mail questionnaires is available (Lundin et al., 1971). Efforts were also made to account for prior hard rock mining experience. Many of the underground uranium miners in Colorado Plateau and New Mexico had previous mining experience, e.g. early miners in New Mexico may have worked in mines in the Colorado Plateau, some may have been hard rock miners from other western mines, while others were coal miners from the eastern U.S.

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Colorado Plateau

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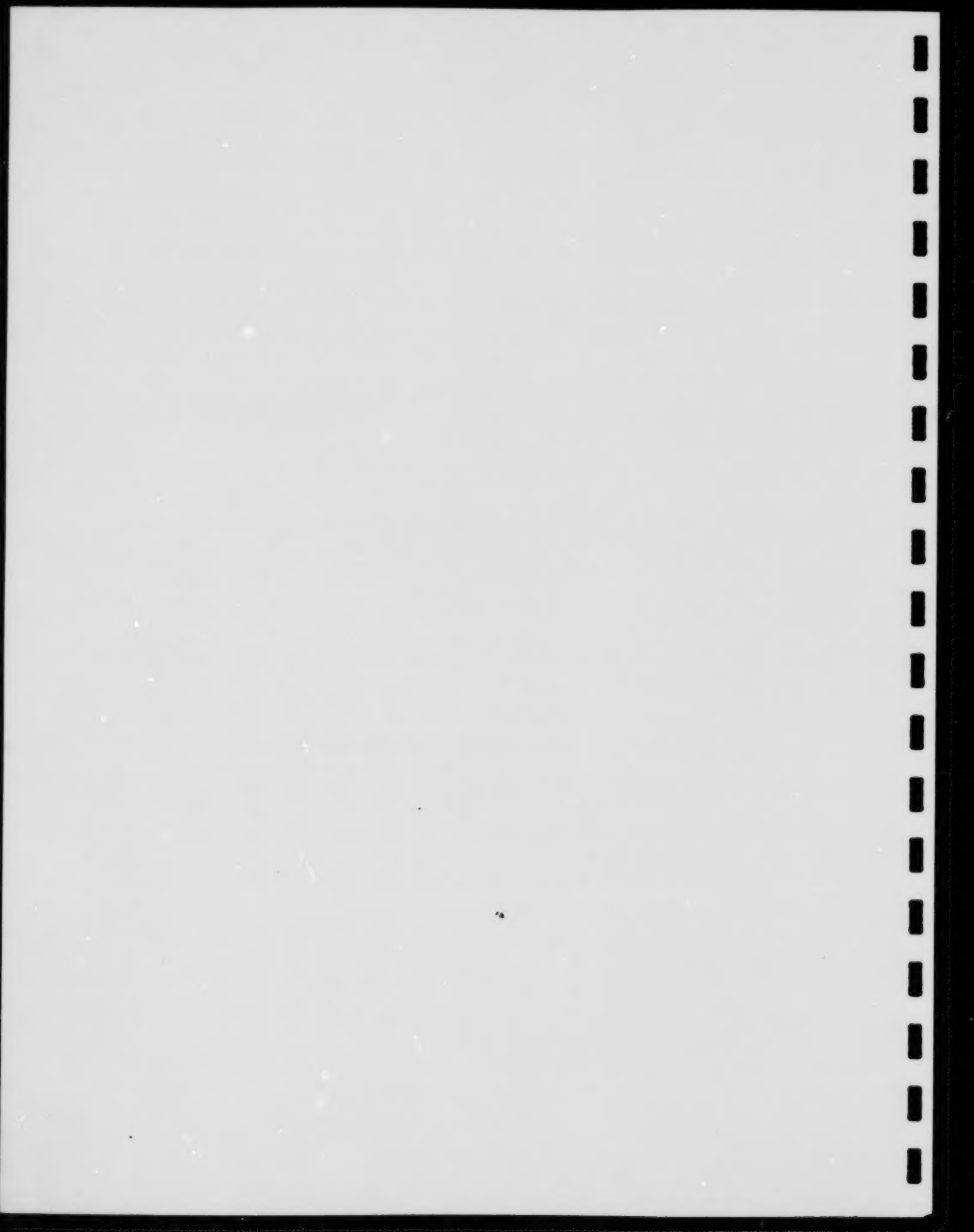
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APPENDIX B: ONTARIO URANIUM MINERS

B.1 History

Uranium mining in Ontario started in 1953 in the Elliot Lake area. Uranium mining in the Bancroft region followed shortly after in 1955. Uranium production developed rapidly to reach a peak during 1957-1960, and declined just as rapidly after 1960. To illustrate, there were 2 operating uranium mines in 1955, 15 in 1958 and 5 in 1964. The period of time during which most high exposures occurred for Ontario uranium miners was relatively short (10 years or so). More than 16,000 men were employed in Ontario uranium mines at various periods during 1955 to 1977 (Muller, 1980). As of 1988, only 2 uranium companies, both in Elliot Lake, operate in Ontario.

In 1954, the ICRP recommended a concentration limit of 100 pCi/L for radon and its daughters. This limit was interpreted in Ontario as being at equilibrium conditions (1 WL of radon daughters) or 12 WLM per year of exposure. This guideline appears to have been used in Ontario from 1955 until 1967, at which time the code on radiation exposure was formally revised to include the 12 WLM/y limit. The ICRP revised their recommendations to a limit of 30 pCi/L in 1959 and subsequently, in 1961, there was a consensus that the limit in Ontario should be gradually reduced (Ham, 1976). The permissible exposure level was reduced to 8 WLM/y in 1973, 6 WLM/y in 1974, and to the present 4 WLM/y in 1975.

B.2 Nature of Measurements

Some exposure levels for operating uranium mines in Ontario became available starting in 1955 although no systematic measurements were made before 1958. In 1957, the Ontario

Department of Mines issued codes requiring measurements, including measurements of radon daughters, to be taken in the mines (Ham, 1976). Thus, measurements, however infrequent, were made in each operating mine. Records of weighted averages of radon daughter levels show that 9 of the 14 operating uranium mines in Ontario exceeded weighted average exposures of 12 WLM/y in 1959. In all the remaining mines except one, the weighted exposures were well above 4 WLM/y (Muller, 1980). For the period 1955-1981, there was an average of 929 radon daughter measurements per mine-year, although the average was only 136 measurements per mine-year up to 1967. Muller et al. (1987) gives details on the historical frequency of measurements.

Exposures for the period of 1955-1967 were based on area monitoring only. Beginning in 1968, personal exposure records became available (Muller et al., 1981). Weighted averages from measurements made in representative areas of each mine were calculated for each year. Tabulated values can be found in Ham (1976). The Kusnetz method to measure radon daughters was used, although until 1967 readings were recorded in radon equivalents (pCi/L) rather than in WL (Ham, 1976).

In 1985 a study to reconstruct underground uranium mining environments was undertaken (DSMA, 1985). Mining practices which existed during late 1950s and early 1960s in the Elliot Lake area were imitated in reconstructed underground mines. Extensive measurements were made in these areas.

Radon daughter levels under various operating conditions were recorded. Under continuous ventilation with compressed air (the most favourable conditions), the exposures in the 1950s were not likely more than double the exposures of today's miners, although in unventilated areas, the exposures could be as much as 10 times higher (DSMA, 1985). The largest uncertainties in estimating

historical exposures were the uncertainty about exposure durations per work task and the uncertainty about ventilation conditions. The study concluded that a typical raise miner in the 1950s, relative to today's miners, would be exposed to radon daughter levels three times higher, equal for thoron daughters and gamma radiation, but much higher for uranium and quartz dust. These retrospective measurements also confirmed that the exposure values used for early years (specifically raise miners) did not overestimate the working exposures during that time.

B.3 WLM Exposure Estimates

B.3.1 Epidemiological Background

Because measurements made during early mining years were minimal, personal exposures for the period of 1955-1967 were constructed from the annual radon daughter levels for a designated mine. Average exposures were recorded in WL units, and WLM units were simply obtained by multiplying by 12 (Ham, 1976). For the years before 1958, all exposures were based on values extrapolated from subsequent years. In 1958, the amount of data based on extrapolation declined, with the final result that only 23% of the total population exposure assigned to the miners is based on extrapolation (backwards in time) (Muller et al., 1987).

From 1968 on, personal exposure data were used. These were obtained by "multiplying the number of hours a man spent in a day in each location with the concentration in this particular location in the mine" (Muller et al., 1983). The exposures were added up over each year and converted to WLM.

In 1980, the first of a series of papers describing the ongoing epidemiological studies of Ontario uranium miners became available (Muller et al., 1980, 1981, 1983, 1984, 1987). The

latest study (1987) extends the period of follow-up to the end of 1981. The basis for the exposure estimates are given in Muller et al. (1983, 1987). In many cases, radon daughter concentrations in mines in the early years of uranium mining were felt to be underestimated. As a result, the recorded concentrations were considered to represent the "lower bounds of the true concentration" (the standard WL). Upper bounds on the concentrations (the special WL), estimated by a group of mining engineers familiar with Ontario miners, were also developed. All calculations for exposures in 1955-67 were carried out for both the standard and special WL limits. Beginning in 1968, personal exposure data were used.

An obvious question regarding these personal exposures of uranium miners from 1955-1977 was how the upper bounds were generated. There were no justifications or explanations found in Muller et al. (1983). Furthermore, it has been suggested elsewhere (DSMA, 1985) that early exposures were not overestimated.

B.3.2 Miner Employment History

Compared to other uranium miners (e.g. U.S. Czech), Ontario uranium miners are characterized by relatively low exposures over relatively short periods of time. Most of the miners started work in the late 1950s. The Ontario mining industry was frequently subject to changes in market conditions. Mining companies and miners moved from mining one ore to another and mining in one location to another (Muller et al. 1983).

The present uranium mining cohort consists of men who worked for one-half month or more in an Ontario uranium mine between 1 January, 1955 and 31 December, 1977 (Muller et al., 1983). The exclusion of those with known asbestos exposure and with exposure in non-Ontario uranium mines reduced the cohort to 15,984 men.

It was discovered that 66% of these miners had other hard rock (OHR) mining experience and that OHR, particularly gold mining, increased risk factors significantly (Muller et al., 1984, 1987). Exclusion of these miners with OHR mining experiences reduced the cohort to 5,443 miners (Muller et al., 1983).

The miners were all requested to fill in detailed employment information of the first 60 months of mining experience (Muller et al., 1981). It was intended to exclude miners with other previous exposures. Mining practices were accounted for in two ways. For the period of 1955-1977, full-time miners were assumed to spend 80% of their working time underground, and 20% on travelways. Part-time miners were assumed to spend 50% of their time underground where more extensive exposures were received. A working history factor (WHF) was also introduced to correct for overtime or work stoppages during the year (Muller et al., 1983). Further details are given in Muller et al. (1987).

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APPENDIX C: CZECHOSLOVAKIAN MINERS

C.1 History

Mining in Joachimsthal, Czechoslovakia started in the beginning of the 16th century. Silver, iron, and copper were first mined. This was followed by mining for cobalt, arsenic, bismuth, and nickel. In 1909, mining of pitchblende started in Joachimsthal. Between 1909 and 1925, Joachimsthal was devoted to pitchblende mining in pursuit of radium and averaged an annual production of about 26 g radium (Lorenz, 1944).

Mining conditions in early years were poor. The mines were usually damp (especially in snow melting season) and cool. Miners had to descend ladders many hundreds of feet to their working areas. Ventilation was provided by a gallery between all mines, and, according to Lorenz (1944), it was generally "sufficient" except at dead-end shafts.

Although high death rates among miners in their prime years caused by lung-related diseases were recognized and recorded as early as the 1600s, no extensive studies were done. In 1879, Harting and Hesse became the first to conduct organized investigations on Schneeberg workers (German). They reported their findings of 20 necropsies. They found that 75% of the deaths were caused by malignant growths in the lung, and that the incidence was greater among miners than in masons or carpenters working in the mines (Lorenz, 1944). (They actually counted, from 1869-1877, 150 deaths due to "miner's disease" out of a work force of 650 men.) The onset of the disease occurred after about 20 years' work in the mines. According to Lorenz (1944), Harting and Hesse were the first to diagnose "miner's disease" as lung cancer. Because they estimated that a miner inhaled 6 g of dust in 7 hours, they assumed that the inhaled arsenic in the

dust (and poor nutrition) were predisposing factors in the disease.

More investigations followed. In particular, Rostoski and Saupe in a 1921 study of selected miners and non-miners (507 people in all) found cancer of the lung to be a frequent cause of death among miners (Lorenz, 1944).

The first case of lung cancer in Czechoslovakian radium workers was observed by Dr. Pirchan in 1926 in a radium factory worker. In 1929, Lowy reported 2 lung cancer deaths of Joachimsthal miners. As the result, further study of the issue was commissioned by the Ministry of Public Works. In 1929-1930, Pirchan and Sikl (1932) examined necropsies on 13 of 19 miners who died during the period. They stated incidence lung cancer to be highly prevalent in Joachimsthal miners and suggested radium emanation (radon) was the most probable cause. Lorenz (1944), however, later suggested that genetic susceptibility to lung cancer in miners must be unusually high.

Upon realizing that radioactivity could be a major cause of lung cancer deaths among miners, measures were taken to ensure lower exposures. Drilling with water washout was introduced around 1930 (Sevc, 1984) to reduce radioactivity carrying dust contaminants. The Czechoslovakian Health Ministry also started collecting mortality data dated back to 1946 among miners in order to gain a better understanding of the hazards of exposure to radon daughters.

In the 1950s, general artificial ventilation and local ventilation in all sections were brought into all mines systematically. Increased efforts to reduce radioactive contaminants by means of increased ventilation and tighter safety regulations began in 1966 (Vesely and Sada, 1968). Based on

recent discussions with Czech investigators, it appears that prior to 1932 the mines were ventilated using natural ventilation and from 1932 onwards there was some mechanical ventilation. After the World War II, mining more or less started from scratch. Up until 1952 there was some natural ventilation. Mechanical ventilation started seriously in 1953 and, from 1955 onwards, all mines were mechanically ventilated. From 1956 onward, auxiliary ventilation was also provided where appropriate.

Working conditions became better as the correlation between exposures to short-lived radon daughters and lung cancer deaths among miners became better known. Figure C.1, adapted from Vesely and Sada (1968), shows the dramatic reduction in radon concentrations which occurred in Czech mines during the 1950s. The mean cumulative exposure of miners starting work in the years 1968-1972 was estimated to be about 40 times lower than for older miners who started work in the interval (1948-1952) (Sevc, 1984).

C.2 Nature of Measurements

Pirchan and Sikl (1932) reported that there were three active miner "pits" in Joachimsthal during the time. The quantity of radium emanation (radon) found in the air discharged from Harmony pit (depth 500 m) was 4 mache units, Werner pit (476 m) 15 mache units, and Saxon Nobility pit (120 m) 10 mache units. (One mache unit is approximately 275 pCi. The unit "per litre" is implied in this unit. See Behounek, 1927.) Pirchan and Sikl realized the variation of radioactivity levels around the mine and thus suggested measurements in various locations should be made. Lorenz (1944) makes similar observations.

Water has often been reported as a large source of radon in underground mines. The Czechoslovakian mines were no exception. For example, Behounek (1927) reported radon in groundwater at

levels up to 426,000 pCi/L in the Joachimsthal mining district.

Systematic radioactivity measurements did not exist in Joachimsthal until the later 1940s. From 1948-1960, radon concentration measurements were recorded. There were hundreds of readings for each uranium mine per year available during this period (Sevc and Placek, 1972). The method used to measure the radon consisted of the "classical" method of measuring, with an electrometer, the current in an ionization chamber (Sevc et al., 1976). The measurement of radon daughters did not begin in Joachimsthal until 1960 (Sevc, 1976); and in 1968, personal exposure records, which took working place and work time into consideration, were recommended as the measuring method. The records were corrected quarterly for each individual and reported as such (Swent, 1984).

Average radon concentrations measured in Czechoslovakian uranium mines between 1949 and 1964, shown on Figure C.2, were kindly provided by Dr. J. Muller (1981). The numbers of samples on which the averages were based are also illustrated on the figure.

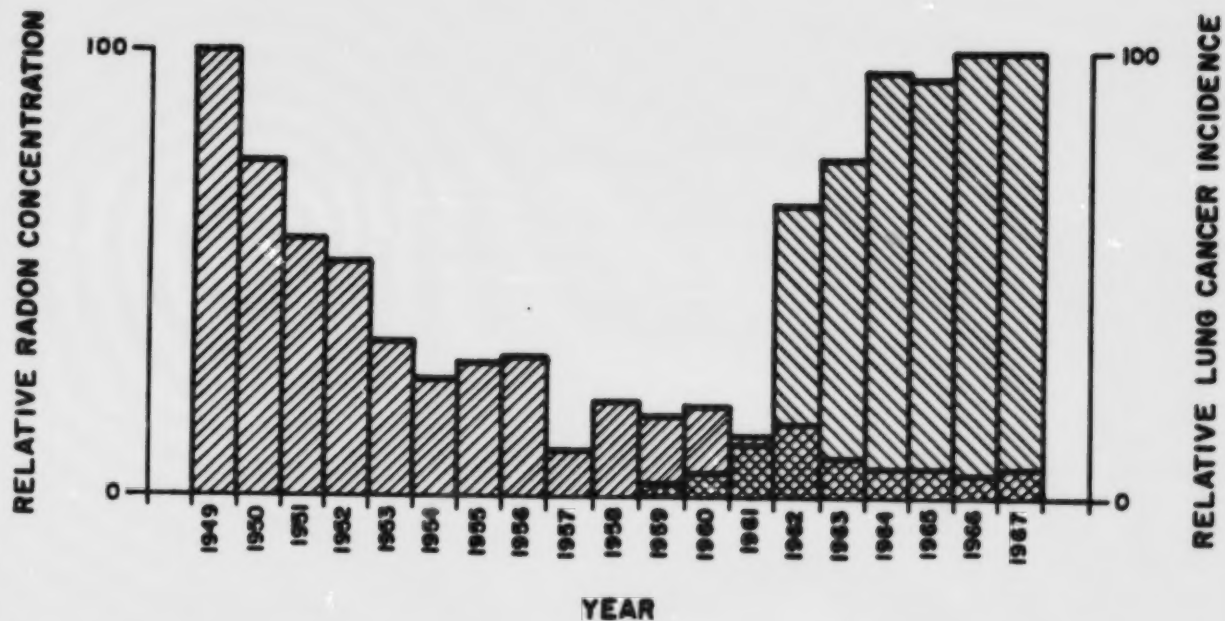
C.3 WLM Exposure Estimates

C.3.1 Epidemiological Background

The Czechoslovakian epidemiological studies on uranium miners were primarily carried out by Sevc and others (see bibliography, C.4). The first study was reported by Sevc et al. in 1971 and there have been several updates, with the last published in 1988.

In the 1972 study by Sevc et al., a random group of miners were selected. The miners were chosen to represent approximately 11% of underground miners in representative mines. There is a major difference, compared to other epidemiological studies, in which

FIGURE C.1
**AVERAGE RADON CONCENTRATIONS
 AND THE INCIDENCE OF LUNG CANCER
 IN CZECHOSLOVAKIAN URANIUM MINES
 (1949-1967)**



LEGEND:

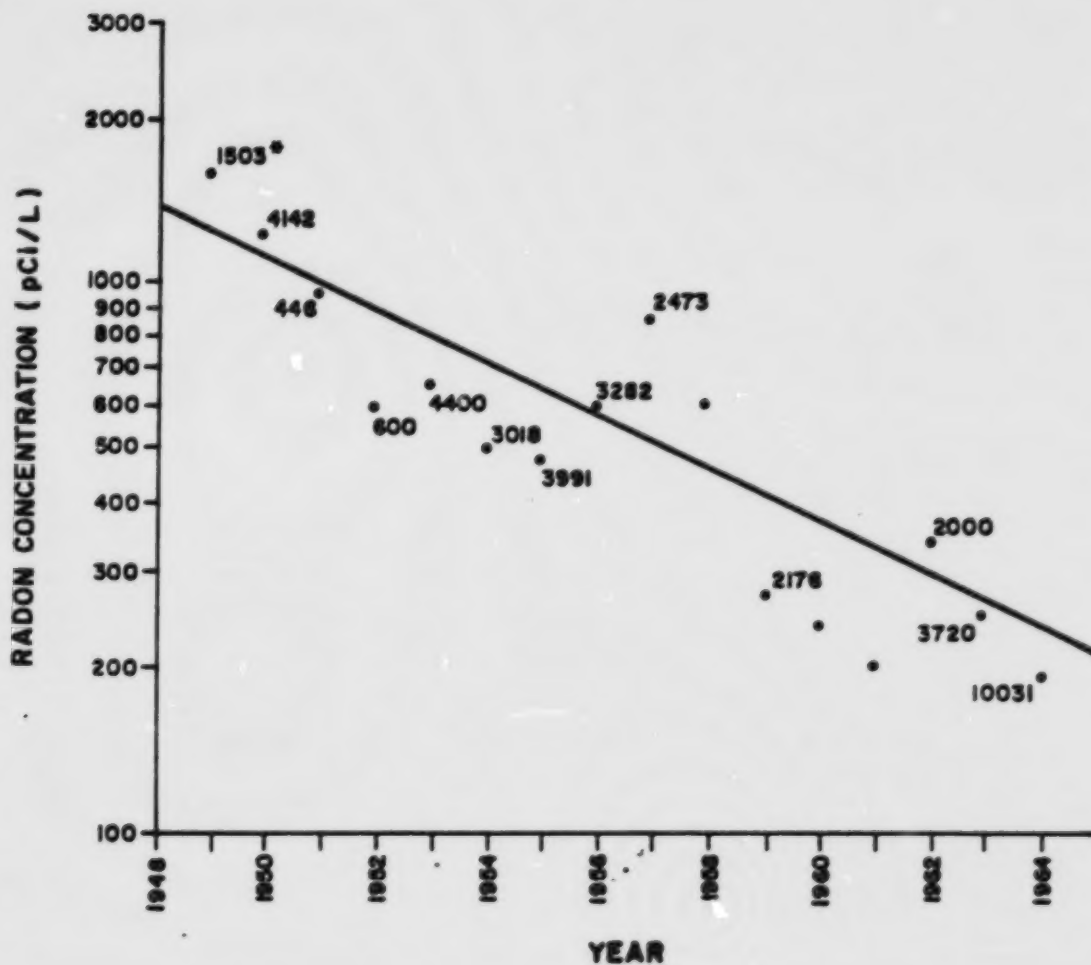


AVERAGE CONCENTRATION OF RADON (1949=100)



OCCUPATIONAL LUNG CANCER (1967=100)

FIGURE C.2
RADON CONCENTRATION
IN CZECHOSLOVAKIAN URANIUM MINES
(1949 - 1964)



NOTE:

1. (*) FIGURES INDICATE THE NUMBER OF SAMPLES ON WHICH YEARLY AVERAGES ARE BASED

the accumulation of WLM exposures are handled in the Czechoslovakian studies. For example, in Sevc et al. (1976), person-years at risk are assigned to the final WLM category reached by each miner rather than being distributed across each WLM interval as they accumulated. This affects the estimation of expected lung cancer cases in each exposure category. This difference was discussed by Kunz and Sevc (1978) who re-evaluated their epidemiological data according to the more conventional (U.S.) method. They concluded that the distortion caused by earlier methods were not large. The more recent analyses (Kunz et al., 1978, 1979; Sevc et al., 1988) use the conventional approach.

One paper by Sevc et al. (1976) became the basis for many later studies. It involved 2 groups of miners - group A consisted of miners who started uranium ore mining between 1 January 1948 and 31 December 1952, while group B consisted of uranium miners who started mining between 1 January 1953 and 31 December 1957.

According to Sevc et al. (1976), the smoking characteristics of every miner was not unusual. Investigation of a random group of 700 miners showed that 70% were smokers, the same as the general male population of Czechoslovakia. They thus concluded that the use of general mortality estimates was appropriate.

C.3.2 Exposure Estimation

Sevc et al. (1976) reported that "...estimates of working levels of radon daughters (WL) for radon gas concentrations were made on the basis of records of the ventilation conditions and practices, emanation rates from different types of ores and radon daughters measurements made in 1960 and later", and also "...the values for working levels months (WLM) were estimated on the basis of radon gas measurements and from data on the number of months of employment with each mine and within each calendar year of the

whole employment period for each miner." No further details of how each factor was accounted for was given. However, the authors assessed the coefficients of variation for working level to be less than 27%, and that of working levels months (WLM) to be less than 30%. In our view, workplace to workplace variability and variation between mines, coupled with uncertain work histories (See C.3.3.) suggest that the Czechs may be somewhat optimistic with regard to the confidence they place in their exposure estimates. (Even with the benefit of recent discussions with the Czech investigators we retain the view that they may be overly optimistic with regard to the precision they assign to estimates of exposures to individual miners. The variability about the mean WLM for a group of miners is however likely to be small.)

Swent (1984) gives some details on the methods of determining exposures. The mean average radon daughter concentration (WL) in each mine was used to calculate each man's exposure based on his working time. Payroll cards were available for all men in the study groups. Since 1968, individual personal dosimetry cards were used to record each miner's exposure. Apparently, studies to use personal, solid state dosimeters are proceeding. (Recent discussions with the Czech suggest that exposures estimated using time-weighted area measurements and personal dosimetry are unlikely to differ by more than a factor of 2.)

Since very few measurements of workplace exposures of any kind were available prior to 1948, estimation of exposures requires consideration of many factors, including radiation levels recorded in later years, early mining practices and ventilation systems. (In recent discussions, the Czechs indicated that Group S miners do not include men with pre-1949 exposures and therefore this aspect is not an important factor.)

The most recent epidemiological study (Sevc et al., 1988) reports on two major study groups: Study S (combined groups A and B) which consists of miners who were first exposed in 1948-1957; and Study N which consists of uranium miners who were first exposed after 1968.

Equilibrium factors are necessary to convert radon concentrations measured in 1948 - 1960 to radon daughter concentrations and subsequently to WLM exposure used in epidemiological studies. This is an important factor as no radon daughter measurements were made prior to 1960. The relatively modern ventilation conditions that existed at the time the equilibrium factors were evaluated could result in estimates for the equilibrium factors that are too low. In recent discussions, the Czechs have indicated that they have used the results obtained during two ventilation accidents when ventilation was shut down as the basis for the assessment. Knowledge of mining methods, ventilation and theoretical predictions also contributed to the evaluation of past exposures.

C.3.3 Miners' Employment History

The employment history of the miners is a very important factor in estimating exposures.

Joachimsthal is situated in Erzgebirge (Ore Mountain), where abundant minerals are found. As discussed in Section C.1, there was a long history of mining before pitchblende was first mined in 1909. It appears likely that the early miners had previous mining experiences (e.g. Lorenz, 1944; Pekarek et al., n.d.).

Pirchan and Sikl (1932) found Joachimsthal miners' occupations subject to frequent changes. They only indicated the predominant occupation in their paper. No other miners' employment history

search was reported in the published papers. Even though the Czechs referenced U.S. authors who did conduct employment history studies among Colorado miners, it remains unclear how Sevc et al. carried out their studies on employment history. With a latent period (calculated from a fixed point in time - start of mining - which may not be appropriate) averaging 16 to 18 years for Czech miners (Sevc and Placek, 1973), early exposures, be they from a uranium mine or not, might be the most influential record in a miner's health history.

As all mines were relatively close to each other, miners often worked in different types of mines. In this regard, Pekarek et al. (n.d.) note that there was a high turnover in mining personnel: "During an observation period in the last several years, it was found that there was a 100% annual employee turnover at this mine." In the epidemiological studies of Sevc et al., selected miners were recorded for the dates which they entered uranium mining. Their previous mining experiences and exposures were not researched and thus were not accounted for in the WLM calculations.

Pekarek et al. (n.d.) report radon measurements in the air of various non-uranium mines of Northern Bohemia. In one of the mines (Mine A), over 90% of the samples taken in 1965 exceeded 200 pCi/L. Pekarek et al. also suggest that equilibrium conditions in the mines are upset by inadequate ventilation and that it is "more convenient" to measure the potential energy than radon alone. (However, Sevc et al. (1984) state that less than 2% of the epidemiological study group mined non-uranium ores before they mined uranium.)

Job mobility concerns not only mobility among different mines, but also different locations and different jobs within the same mine. It is only the nature of a miner's job to move around

within a mine. Vesely and Sada (1968) attempted to categorize each patient (miner employed between 1944 and 1947) into a specific trade or job throughout his entire employment. They found over 50% of the cases not classifiable.

Because radon daughter concentration fluctuate from one location to another within a mine and also from one time to time at the same location, there exist areas of relatively higher and lower exposures within a mine. Pekarek et al. (n.d.) emphasize this point noting that, "Besides total measurements, one must consider the radon values measured directly in mining chambers, which are the most exposed work sites of the mines." For example at Mine A noted previously, Pekarek et al. (Table 1, 1984, pg. 15) indicate that radon levels in the mining chambers were in the order of 517-659 pCi/l (for the 1965-1967 period). They also state that 8 out of 11 miners with cancer worked in mining chambers under the least beneficial working conditions. Knowing the distribution of time spent in high and low exposure areas would contribute to a more accurate exposure estimations. This information can only be obtained by learning about the general pattern of mining practices during the period of interest.

Another element which should be considered in WLM calculations is the time spent by a miner at work. By definition, a "working month" now conventionally means 170 hours of work. If a miner held more than one job with a mine in 1920s through 1950s, the additional working hours and hence exposures need to be taken into account. Sevc et al. (1976) state that only the number of employed months during a year were taken into consideration. There was no evidence from the publications that the miners working patterns were incorporated in the WLM estimations. In recent discussions with Czech investigators, the Czechs noted that the workers spent about 80% of their time in the workplace and 20% in travelways. In early days, the men worked 8 hour

shifts (3 shifts per day), 6 days per week. After 1968, the normal working week was reduced to 5 days. Uranium miners had a total of 5 weeks per year off work. Retirement from uranium mining is now mandatory at age 50, but retired uranium miners often continue to work in other (especially coal) mines. After 1966, people over 40 years of age were not accepted into uranium mining as new miners.

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APPENDIX D: BEAVERLODGE MINER STUDY

The study of Beaverlodge uranium miners has been discussed at some length in the text of this report. This Appendix provides a few additional comments on the Beaverlodge miner study and identifies some supplemental bibliographic materials.

D.1 History

Frost (1983), in Draft #4 of the Beaverlodge working level month (WLM) calculations, provides a brief description of the history of the Beaverlodge mine. According to Frost, the Ace shaft was started as a prospect shaft in 1949, and by 1951 Eldorado had identified sufficient ore reserves to proceed with the production operation. By that time, ore bodies to the west of the Ace shaft had also been identified. In 1951 the Fay shaft was started as a production shaft serving the western ore bodies. An underground haulage way also provided access to the Ace ore body.

Mill construction started in 1952 and the first uranium concentrate was produced in the spring of 1953. According to Frost (1983), the Verna ore body to the east of the Ace shaft was identified and work started on the Verna shaft in 1953 with production starting in 1956.

As the mine developed, all three shafts were connected underground and two winces, shafts which do not come to the surface, were developed. By the late 1970s, the mine complex was over one mile (1.6 km) deep and extended over three and a half miles (5.6 km) horizontally.

A number of small satellite mines, most being small open pits, were also developed through the 1960s and 1970s. Two underground mines were also developed, Hab and Dubyna, both of which were

located a few miles north and east of the Verna shaft.

A cut and fill operation was used in which ore was removed at the bottom and mining advanced upward from one level to the next. The sand fraction of the mill tailings was used as backfill in the mine, with miners working off the backfill to remove the next lift. Simpson et al. (1959) investigated this activity as a possible source of radon and concluded "no positive evidence was found that backfill was a major source of radon in the mine" (ibid, pg. 85).

Mining production in the Uranium City area of Saskatchewan increased rapidly through the 1950s falling off in the early 1960s as the demand for uranium declined. According to Garbut (1964) there were a number of uranium mines operating in the Beaverlodge Lake area of northern Saskatchewan (see Table D.1). An even larger list of uranium mines in the Uranium City/Beaverlodge of northern Saskatchewan is provided in Figure 43 of a report by Kupsch (1978). This observation is important since, because of the remote location, the cost of recruiting in the Beaverlodge/Uranium City area was high. Consequently, Eldorado's policy was to recruit experienced miners whenever possible. As the local uranium mines closed and as Eldorado remained in production, there were opportunities for miners with non-Eldorado working experience to migrate to the Beaverlodge operation.

Most of the mines in the Beaverlodge area operated only for a few years and all were shut down by the later 1960s. Most of the mines were small operations without mechanical ventilation (the exception being the Gunnar Mine) and hence there was a potential for very high exposure even in a short time period.

The Beaverlodge operations were closed in June 1982.

D.2 WL Data and WLM Estimates

As noted by Frost (1983), as the mining operations at Beaverlodge were coming into production in the early 1950s, radon daughters were just starting to be recognized as a potential health hazard.

In 1954 and 1956, surveys of radiation levels, dust and general ventilation conditions were performed which eventually resulted in routine programs for radon/radon daughter measurements. Initially the measurements were made for the purpose of engineering control. Over time, increasing numbers of measurements especially for radon daughters were made by Eldorado's ventilation department for the purposes of employee exposure control.

In 1967, Eldorado started to maintain personal records of radon daughter exposure for full shift underground workers. Workers' time cards indicated the hours spent in each work place. These cards were consolidated into a computer printout of monthly manpower working places. This printout, together with measurements made in the workplace and the travelways, was used to estimate monthly radon daughter exposures.

In 1970, the computer record system was expanded to include cumulative exposure in the exposure summary reports. At this time, records of previous engineering measurements (as opposed to the measurements for the purposes of estimating miners exposures) were used to back-calculate exposures to 1 November 1966. Each month, when the individual exposure calculations were done, lifetime totals were also calculated.

In September 1971, all maintenance, technical, supervisory and other personnel who had received some radon daughter exposure were added to the exposure role. Their exposures were back-

calculated to 1 November 1966 using mine average working levels and hours worked per year and a factor to account for the portion of time spent underground.

Frost (1983) notes that the median was used to represent WL exposure levels in the mine. Frost (1983) is cited by Howe et al. (1986) as the source of the exposure data used in their analysis. Prior to publication of the Howe et al. paper however, Frost had already re-thought his approach and concluded there were some serious errors in the exposure estimates, especially the use of the median rather than the average value to characterize workplace radon daughter levels. There were also deficiencies in miners work histories.

Most recently, Frost has attempted a limited review of the radiation exposures of Beaverlodge miners (Frost, 1989). Frost carefully re-examined several years of data, taking care to eliminate samples from unoccupied idle areas and to separate the exposure data into workplace and travelway measurements. Mine-wide, mean annual WL values were recalculated using this exposure data assuming that 80% of the miners' time was spent at workplaces and 20% was spent in the travelways, as in the earlier studies. In Table 2 of his paper, Frost (1989) notes that the differences between the original epidemiological estimates and his revised estimates decrease with time from 1954 through 1961, by which point the two estimates are nearly equal.

To test the effect of his recalculation, Frost (1989) calculated the cumulative exposures of a sample of 78 miners. Of the 78 miners, 28 had no change in exposure because they were employed after 1961. Nonetheless, the arithmetic mean exposure for the group of 78 increased from 26 WLM to 61 WLM, or by more than a factor of 2.

Frost (1989) also examines other assumptions used in the study of Howe et al. (1986) concerning other mining experience including other uranium mine exposure. Overall, Frost concluded that the exposures of the epidemiological study may be underestimated by a factor of 2 to 3.

D.3 Miners' Employment History

Possible discrepancies in employment histories of the Beaverlodge miners have already been noted in the text of the report and therefore are not discussed further.

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APPENDIX E: PORT RADIUM MINER STUDY

The Eldorado Port Radium mine has a long history extending back to about 1930 when a prospector by the name of Gilbert LaBine identified pitchblende on the north shore of Great Bear Lake. Open pit mining started shortly thereafter and the first pitchblende was shipped by 1931. Underground operations were in full swing by 1933. Mining continued until 1940 when a decreasing demand for uranium ore led to the mine shutdown. In 1942, the Port Radium mine was re-opened at the government's request and it continued in production until 1960 when it was shutdown.

Kupsch (1978) provides a detailed history of Eldorado and the Port Radium mine in particular (Kupsch, 1978, especially pages 52-63). Additional interesting information on the history of Eldorado's Port Radium mine is provided in two papers by J.G. McNiven (1967) in which McNiven reviews the operations at Port Radium from the re-opening of the mine in 1942 to the final shutdown in September 1960.

E.2 Measurements

Port Radium was the first mine in Canada where radon/radon daughter sampling was performed, with the first samples being taken in 1945. Initially, only radon was measured, but by the mid-1950s both radon and radon daughters were measured.

The equilibrium factor between radon and its daughters was in the order of 30% in 1957. It is therefore likely that the equilibrium factor was higher in the early days of mining when there was no forced ventilation.

Annual radon daughter concentrations based on available

measurements and assuming a 30% equilibrium have been estimated by Eldorado to be in the order of 77 WL in 1945, 38 WL in 1952, 10 WL in 1956 and 8 WL in 1957. Unfortunately, however, we are not aware of these exposure data and corresponding miner exposure estimations having been published in the open literature.

E.3 Epidemiological Analyses

Recognizing that the early miners had a potential risk of lung cancer, Eldorado sponsored a pilot epidemiological study of Port Radium workers. This study (Grace et al., 1980) indicated that there was an excess of lung cancer in miners who had five years or more of underground experience.

Consequently, Eldorado initiated a much more detailed epidemiological study which involved the assembly of radiation exposure data by Eldorado and which involved Statistics Canada and the National Cancer Institute of Canada who actually performed the epidemiological analysis. The results of this analysis have been reported by Howe et al. (1987).

According to Howe et al. (1987), the Port Radium mine operated with only natural ventilation until 1947 when a 22,000 CFM fan was installed. In 1957, forced air ventilation capacity was increased to 35,000 CFM. However, Howe et al. (1987) note that winter heating problems still caused a drastic reduction of ventilation until 1958 when additional improvements were made.

According to Howe et al., radon gas samples were collected for seven years between 1945 and 1958, with between 9 and 71 samples per year for a total of 251 samples. The range of concentrations was reported as 50 to 300,000 pCi/L.

In the Port Radium study, unlike the Beaverlodge study, the

investigators in at least some circumstances used the annual average rather than the median to represent radon daughter levels.

Howe et al. (1987) also identify various reasons for their conclusion that the exposures of the Port Radium miners are likely underestimated, stating that "therefore the present coefficients may be treated as an upper limit of the true risk coefficients" (ibid, pg. 1259).

Finally, Howe et al. (1987) cite Frost (1983) as the source of their radon daughter exposure data.

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APPENDIX F: FLUORSPAR MINERS

The Newfoundland Fluorspar miner data has been reviewed in the text. The 1969 report of the Royal Commission provides a wealth of interesting historical data.

F.1 History

Fluorspar is the only mineral resource known to be of economic quality in the St. Lawrence, Newfoundland area.

For many years, St. Lawrence was an isolated fishing community. Shortly after World War I, the community was devastated by the drop in price of salt-cured fish (the main source income) and by the destruction of all of the fishing equipment by the tidal wave in 1929. Mining took over as the principal occupation when it began to develop in 1933 (de Villiers et al., 1964).

The mining method initially was open cut but shafts were later used to extract ores. Standard underground mining procedures were adopted with the first underground mine in 1936. Wet drilling becoming generally accepted in 1942. Shrinkage stoping and cut-and-fill methods were not practiced until after 1964. The underground mines were in general very wet. Ventilation was mostly provided by natural drafts. Except in one case, supplementary blowers were not used until 1946 (de Villiers, 1971).

The hazards of St. Lawrence mining began to receive recognition in the early 1950s; the first miner died of lung cancer in 1949, and this was followed by several more lung cancer deaths (Wright et al., 1977). Epidemiological and clinical investigation began in 1956. It was not until 1959 that the first radiation survey revealed very high levels of radon daughters (Morrison, 1984).

Windish (1964) suspected the source of radiation to be either radon from uranium embedded in host rocks escaping through cracks and crevices into working places, or radon brought in from outside sources into the mines, possibly by water. The source of radon was later confirmed to be mine water (de Villiers et al., 1964).

Beginning in 1969, after discovery of the environmental problem in fluorspar mines, ventilation was greatly improved to reduce the radon daughter concentrations to well below the suggested limit of 1 WL.

In 1978, the last Fluorspar mine closed in St. Lawrence, Newfoundland. By this time, 78 cases of lung cancer had been identified (Corkill and Dory, 1984).

F.2 Nature of Measurements

The surveys conducted by Windish and Little in 1959 and 1960 collected 17 radon, 80 radon daughter and several gamma radiation readings. The method used to determine the radon daughter concentration was that described by Kusnetz (1956). Kusnetz determined that his method under conditions of extreme non-equilibrium could result in a maximum error of from 12% overestimation to 7% underestimation of the total potential alpha energy to complete decay (de Villiers, 1964). This source of error was relatively small compared to other estimation uncertainties.

A retrospective study of early mining conditions and working level exposures to radon daughters was carried out by the Atomic Energy Control Board (Corkill and Dory, 1984). Based on a detailed study of each mine, including measurement data, mining records, ventilation data, interviews and simulation studies,

high, medium and a low radon daughter exposure levels were assigned to every mine for each operating year (1933-1960). Recall that no radon daughter measurement data are available prior to 1959.

From 1960 onward, radon daughter exposure estimates were available for miners by calendar year (Morrison, 1984).

F.3 WLM Estimation

As described in Section F.2, sources of radon daughter exposure data include: (a) values estimated and assigned to each mine and each calendar year for 1933-60 in a retrospective study by Corkill and Dory (1984), (b) survey data by Windish and Little in 1959 and 1960, (c) personal exposure data starting 1960.

The data (80 samples collected at 50 different locations) in Windish and Little's survey formed the basis of de Villier's epidemiological studies in 1964 and 1971. In 1964, mortality among fluorspar miners was compared to the normal mortality in the same geographic region, and other uranium miners.

The WLM measurement of exposure for individuals was not used until the 1971 paper. In the 1971 study, analyses were performed on miners as well as drillers and muckers. Pre-1960 exposures must have been included since the mortality analysis started 1933. However, no explanations of how they were accounted for is given. The only exposure data mentioned remained the Windish survey.

After the retrospective study of Corkill and Dory, Morrison et al. (1984) published a more comprehensive study including mortality data from 1933 to end of 1981 on miners employed during the 1933 to 1978 period. The most recent study by Morrison et al. (1988) also relies on the analysis in Corkill and Dory (1984).

F.4 Miners' Employment History

Detailed occupational histories for fluorspar workers were obtained from company records. The records of the 1933-36 period had to be reconstructed from census data, interviews with company officials and company report reviews since they were lost in a fire (de Villiers, 1964). Workers' occupational histories by accumulated hours of exposures and type and place of work were prepared for all men on the employee list (de Villiers, 1971). Occupational history was particularly important for fluorspar miners since all epidemiological studies included surface workers as well as underground miners.

Corkill and Dory's (1984) study assigned a low, a medium and a high exposure for each mine in each calendar year. As they explained, those values did not represent extreme concentrations but were average workplace concentrations for low, medium and high areas. Each type of job usually dictated where a man worked and thus a worker could be placed within a certain average exposure. For example, development miners were assigned the high averages, stope miners the medium averages, and miners working in an established area near an air circuit were assigned low averages. The high and low averages often differ greatly (from 2.5 x to 10 x). To use these averages properly, good knowledge of each workers duties had to be researched.

No mention of job mobility was found. It might have been accounted for to a certain degree since payroll record which was used to construct the occupational history was recorded bi-weekly. However, it remains unconfirmed.

No account of previous hard-rock mining experiences was found. However, since St. Lawrence was an isolated fishing community especially in the early years, workers were most likely fishermen

turned miners without previous exposures.

A working month was considered to be 167 hours by de Villiers and 170 hours by Morrison in WLM calculations. Accumulations of working hours were likely to be reasonable since they were compiled from payroll records (if miners were paid on an hourly basis).

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APPENDIX G: SWEDISH IRON ORE MINERS

The 1984 study of lung cancer in Malmberget iron miners by Radford and St. Clair Renard has been discussed at some length in the text of this report. This Appendix provides some additional information in the general history of iron ore mining in Sweden and some further details specifically related to mining at Malmberget.

The basic reference for the study of Malmberget iron miners is the paper by Radford and St. Clair Renard (1984) in which these investigators describe, among other factors, the basis for the radon exposure estimates. These authors indicate that the major source of radon was radon dissolved in water seeping into the underground mines. These authors also note that the earliest measurements of radon in mine air at Malmberget were made in 1968 and that subsequently extensive measurements of radon/radon daughters in air were made by the National Radiological Protection Institute and LKAB. Radford and St. Clair Renard indicate that a new ventilation system for the mines became operational in 1972. They state that the reconstruction of past concentrations depended on the measurements made during the period 1968-1972 and knowledge of the natural mechanical ventilation used previously. However, the authors go on to note that the reconstruction of Malmberget exposure data depended on "the assumption that ventilation conditions in the mines in the 1968 - 1972 were not greatly different from those in the past..." (ibid, pg. 1486).

In September 1985, Swent and Chambers (1986) travelled to Sweden to visit the Malmberget mine of LKAB and to learn first hand of the experience this mine had with exposure of miners to radon daughters and how exposures were estimated for the period prior to 1968. During the visit, Chambers and Swent also visited the

Kiruna iron mines as well as meeting with several well known Swedish authorities, including the researchers for the Swedish National Institute of Radiation Protection who performed the measurements in the 1968 to 1972 period. Some of the information obtained during this visit is noted in this Appendix.

G.1 History

Iron ore mining in Sweden has existed since medieval times. Originally, there was only open pit mining, but beginning around 1910, underground mining started (Edling and Axelson, 1983).

According to Snihs (1973a), the primary sources of radon in the Swedish iron mines were incoming radon rich water and to a lesser extent radon from radioactive minerals. Snihs (1981) notes that the uranium content in the waste rocks in the iron mines was only of the order of 15-20 ppm.

Before 1945 the ventilation was entirely natural. According to Axelson (1980), some mechanical ventilation was developed during the 1940s and 1950s to avoid freezing of water underground. This was accomplished by taking air through old shafts before reaching work places so that, the ground could heat up the air. However, the air travelling through the old shafts also picked up some radon daughters and because of travel time allowed the ingrowth of radon daughters.

In some mines ventilation air was brought into the mine through crushed rock. This method, although reducing dust and raising inlet air temperatures, also picked up any radon emitted from the crushed rock (Snihs, 1973a).

The first radon measurements performed in Swedish mines were made in the early 1950s in the Boliden mine according to Snihs

(1973a). However, limited knowledge about radon problems in non-uranium mines and a lack of experience in taking measurements delayed the institution of natural radon or radon daughter measurements. The general discovery that many mines had significant radon levels was made about 1968. This led to radon surveys in which the general procedure was to take 3-12 radon gas samples per mine from both winter and summer periods. Samples were collected in evacuated bottles which were then sent to the National Institute for Radiation Protection in Stockholm for analysis.

According to Snihs, each mine whose initial radon gas survey showed radon daughter levels of 0.3 WL or more was investigated further by the Institute who visited the mine and took radon daughter samples using the Kusnetz method, as well as many additional radon gas samples. Typically, more radon gas samples were taken than radon daughters samples. The equilibrium between radon and radon daughters was found to vary greatly but was typically 50%. This equilibrium is referred to often as a dose factor by the Swedes (Chambers and Swent, 1986) .

Having identified the problem, ventilation in the Swedish mines was gradually improved. The ventilation path was changed to bypass crushed rock and incoming groundwaters, thereby, leading to reductions in exposure (Snihs, 1976).

In 1972 St. Clair Renard concluded that there was an apparent excess of lung cancer in three mining communities, all of whom had extensive mining operations.

(In viewing Swedish papers it is worth noting that the Swedes typically do not discuss radon daughter concentrations in terms of WL but most often use the phrase "equivalent radon concentration", in which radon daughter concentrations, expressed

as equivalent radon concentrations, can be converted to WL by dividing by 100, e.g. an equivalent concentration of 40 pCi/L corresponds to 0.4 WL and at 50% equilibrium corresponds to an actual radon concentration of 80 pCi/L.)

Snihs and Ehdwall (Chambers and Swent, 1986) noted that since 1971 the National Institute for Radiation Protection has had no overall mine program other than to occasionally return to a mine and make some check determinations.

The Malmberget mine as it now exists is a combination of several mines which initially were separate mines. The iron ore deposit at Malmberget consists of about 20 different ore bodies. It is composed of various large ore bodies that outcropped to the surface in which several open pits were started. Most of these mines were line with each other separate by low grade iron formation. At one point, either faulting or folding moved one of these ore bodies, "the Kapten", to a point where it is opposite several of the others horizontally removed by several hundred metres.

Open pit mining in the area first began about 1890. Later when the depth of the mining forced the conversion from open pit mining to underground mining (all were underground by about 1930), the bottoms of the mines were still above the general level of the terrain. Thus, the adits could be driven from the side of the mountain to the bottoms of the underground mines, which in turn were connected to bottom of the open pits and therefore permitted natural ventilation of the mines. By 1955 the bottom levels of the mines went below the level of the country surrounding the mountain so that the efficiency of natural ventilation system declined as ever lower levels were developed.

The Malmberget mine is now generally referred to as one of five major groups of mines including Hermelin, Tingvallskulle, Dennewitz, Koskullskulle, and Kapten.

During the visit to Malmberget, Dr. Renard reviewed the history of mining methods and general ventilation in the mines. When the mines were first converted from open pits to underground mines, the underground method of extraction was by shrinkage stopping. Small pillars were left between the large shrinking stopes. After the shrinkage stopes were drawn empty of broken ore, the hanging wall was allowed to cave in and fill the opening. Shrinkage stopping was followed by sublevel stopping system of mining and in 1965 the mining system was changed to sublevel caving. This allowed even larger quantities of wall rock to cave. Until 1973, fresh air was drawn from through the broken rock left above the mining areas by these two methods. While the principal source of radon in the Malmberget mine is likely radon-rich mine water, it is possible that some additional radon entered the mine air via this method of ventilation.

From discussions with mining engineers who worked at Malmberget it is clear that extensive recirculation of air was widely practiced in the Malmberget mine in the 1950s and 1960s. This recirculation could have permitted the build-up of both radon and the equilibrium fraction during that period.

Mining engineers at Malmberget explained that changes of mining methods in the mid-1960s made it necessary to introduce diesel equipment which in turn lead to the requirement to introduce good mechanical ventilation. In October 1969, the Swedish National Radiation Protection Institute did its first radon measurements in the Malmberget mines. As a result of these measurements, there was a recognition that a radiation hazard existed in the mines and therefore a new ventilation system using positive

pressures and doing away with recirculation and the drawing of incoming air through broken rock was designed. The installation of the system began in 1971 and by 1973 was complete. The Malmberget engineers provided a brief tabulation of the mining ventilation histories for the various Malmberget mine groups as shown in Table G.1.

G.2 Measurements

Swedish measurements for radon were typically made using 4.8 litre conventional propane containers by the National Institute of Radiation Protection. The containers were evacuated by the Institute and subsequently opened at places of interest in the mines. After sampling, they were sealed and mailed back to the Institute for analyses in ionization chambers (Snihs, 1981).

Simultaneous measurements of radon/radon daughter concentrations were taken to provide a basis for estimating the equilibrium factor. Typically, an average equilibrium factor was used for all working places in a mine or parts of the mine (Snihs, 1976). According to Snihs (1981), the equilibrium factor varied widely ranging from 0.15 at the air inlet to the mine to nearly 1 at the air outlet. Average equilibrium factors in workplaces were typically between 0.4 and 0.6 (Snihs, 1981). Axelson (1980) however felt a typical equilibrium factor might be more appropriately estimated at 0.7.

Following the first measurements of radon, the mines were divided into zones and checked according to the following frequency:

- Zone 1 - <10 pCi/L (<0.1 WL), once every two years;
- Zone 1 - 10 to 30 pCi/L (0.1 - 0.3 WL), every year;
- Zone 3 - 30 to 100 pCi/L (0.3-1 WL), once every six months.

Table G.1

ROUGH MINING HISTORY AND INTRODUCTION OF DIFFERENT
VENTILATION SYSTEMS* AT MALMBERGET MINES

Years

Hermelin area

(Välskomma, Baron, Hermelin, Johannes, Hens, Josefina Hematite)

~1920

Underground mining probably started in the 1920's. Due to relatively small ore bodies and a lot of hematite ores in these area the mined quantities was comparatively low. Mining method was sublevel stoping and shrinkage stoping. Ventilation with adits and compressed air from drilling equipment. Introduction of sublevel caving with diesel LHD in the end of the 1960's below the 300 m level.

Hens was mined with sublevel stoping down to 400 m level with diesel LHD's.

1960

Fresh air, through Baron personnel shaft (200,000 m³/h) for Baron and Hermelin ores.

1968

Fresh air through broken rock. (300,000 m³/h) for Välskomma, Baron. These years the output was very low.

1973

Fresh air through the F.Ba (= Fresh air shaft of Baron area 150,000 m³/h) replaces the 300,000 m³/h through the broken rock.

1977

Mining activities in the area stops.

Table G.1, continued.

Years

Tingvallskulle area

(Josefina magnetite, Tingvallskulle)

~1920	Underground mining started with shrinkage stoping and sublevel stoping. Ventilation through adits.
1958	Ventilation by big extraction fans. Uncontrolled fresh air through adits, raises and through the broken rock.
1961	Fresh air through Upland personnel shaft 200,000 m ³ /h).
1965	Introduction of sublevel caving with LHD.
1966	Fresh air through the new ramp (FO) from the surface (+ 200,000 m ³ /h).
1967	Complementary ventilation through broken rock (+300,000 m ³ /h).
1970	Another 200,000 m ³ /h through the ramp.
1973	Fresh air through F Upl (=Fresh air shaft of Upland 1,500,000 m ³ /h replaces the 300,000 m ³ /h through the broken rock.
1975	Fresh air shaft F13 adds another 500,000 m ³ /h to the Tingvallskulle area.

Table G.1, continued.

Years

Koskullskulle

This mine was owned by a separate company until ~1957, that's why Dr. Renard have so good control of the persons who worked there because they didn't change from one part to the other to the Malmberget ores.

-1920

Underground mining started with sublevel caving. The ore is situated quite low on the ridge (surface ~230 m level) which means that the adits was only used for about 50 m of mining. When the mining went deeper than the adits personnel and hoisting shafts were connected to the adits.

Ture Jonsson told me that he telephoned to the retired mining manager and discussed the ventilation system with him. The natural ventilation of the Koskullskulle mine was so good so they measured an air speed of ~18 m/s in the adits.

In 1955 dust measurements started all over the Malmberget mine and the highest values was found in the Koskullskulle mine which led to an installation of fans sucking air to the exhaust shafts.

1967

When sublevel caving with LHD started, the F12 fresh air shaft was put in production 1967

1980

(400,000 m³/h) and another 200,000 m³/h was installed 1980.

Table G.1, continued.

Years

Dennewitz area

(Northern Allianzen, Dennewitz, Parta)

- 1920? Start of underground mining.
- 1963 Fresh air through an auxiliary shaft
(capacity ?, probably 200,000 m³/h).
- 1966-67 Introduction of sublevel caving with LHD.
- 1966 F9 fresh air shaft 600,000 m³/h.
- 1974 F9B fresh air shaft adds 600,000 m³/h.
- 1979 Capacity increased with another 600,000 m³/h.

Kapten area

- 1920 Start of underground mining with sublevel
and shrinkage stoping.
- 1955 Fresh air through the broken rock, capacity?
- 1960 Fresh air through the kapten shaft, capacity?
- 1968 Sublevel caving with diesel LHD. F11 fresh
air shaft, capacity 700,000 m³/h.
- 1974 F14 fresh air shaft, capacity 900,000 m³/h.

Note:

- * As provided to Swent and Chambers (1986) by Mining Engineers
from Malmberget iron ore mine.

For areas with levels greater than 1 WL, measurements were to be taken every three months according to Snihs (1976).

Chambers and Swent (1986) concluded that the estimation of pre-1969 WL values by Radford and St. Clair Renard are likely underestimated (by a factor of 2 or so) as they did not take into account or are not consistent with:

1. earlier practice with recirculating air in the mine
2. the lower volumes of air circulated through the mine in earlier decades
3. periods of stagnant ventilation air flow which occurred during the times when natural ventilation was the only ventilation method, and
4. the pattern of decline in the incidence of silicosis.

G.3 Miners' Employment History

Radford and St. Clair Renard (1984) identified miners using company and union records of active and pension miners. These records have been available since 1900. Some men were sought out for medical surveys and a few from parish records. The Swedish government gives every person a code at birth. This code is included in all work and hospital records. Every citizen is required to register in a local parish of the state church. According to Radford and St. Clair Renard (1984), these regulations helped to locate miners and their records.

Also available from company records dating to 1900 were the total number of man-hours worked underground each year in each section of the mine. However, the exact location of the work within the mine is not available.

Radford and St. Clair Renard assumed that the miners worked 173

hours per month on average in the period 1890 to 1930; 162 hours per month during the period of 1930 to 1950; and 144 hours per month from 1950 on.

It is possible that there is some confusion as to work status for miners who started or stopped work or changed work function midway through the year.

G.4 Natural Radon Levels

Epidemiological studies of Swedish miners may be complicated by the high radon levels found in some dwellings. Measurements in the order of 1-10pCi/L were not uncommon (Axelson and Edling, 1980). Consequently, at-home exposures had potential to be both variable and high, thus possibly confounding somewhat the assignment of total exposures to underground miners.

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Appendix H

Estimating Risk of Lung Cancer from Exposure to Radon Daughters – A Regression Model With Errors in the Independent Variables

H.1 Introduction

The studies of radon daughter exposed miners provides a direct, and therefore most often preferred approach for the assessment of human risks. Several such studies are described in the text (Chapter 2) and in Appendices A through G. It is clear that in all of these studies there is uncertainty about the exposure of individual miners or of groups of miners.

Various possible sources of uncertainty are discussed elsewhere in this report (Chapter 3) and will not be discussed further here. The sheer fact that this uncertainty about the miners' working level month (WLM) exposures exists has important implications. This is so, because as described below, normal regression techniques assume that the independent variable (here exposure in WLM units) is precisely known. In this Appendix, a linear regression model which permits errors (uncertainty) in the independent variable is developed. The model also allows for Poisson uncertainty about the value of the dependent variable (here cases or excess cases of lung cancer).

A typical set of data for incidence of lung cancer in uranium miners is given in Table H.1. It shows the observed and expected numbers of cases for six different exposure classifications for a group of American uranium miners (actually Colorado Plateau uranium miners with mining experience as uranium miners only). Details of the exposure of each class are also given.

Two empirical models are typically used to explain the excess risk caused by the radon daughter exposure. The absolute risk model is:

$$\frac{O - E}{PYR} \times 10^6 = \alpha_1 + \alpha_2 \bar{x} \quad (H.1)$$

while an alternative model, the relative risk model, is

$$\frac{O - E}{E} \times 100 = \beta_1 + \beta_2 \bar{x} \quad (H.2)$$

In both of the above O is the observed number of lung cancer cases in an exposure group of miners in a given time period, E is the expected number in the same period, PYR is the number of person years of exposure in the group being considered, and $\bar{x}$ is the average intensity of exposure in the group, measured in working level months. (Note, that in the example given

Table H.1: Incidence of Lung Cancer in a Group of Miners

Exposure Category (WLM)	Observed Cases	Expected Cases	Person Years	Average ¹ Exposure	Standard Deviation of Exposure	Number of Miners
0-119.9	3	4.78	10834	52.6	35.4	427
120-359.9	11	5.23	10850	229.7	69.2	456
360-839.9	17	5.43	9994	571.9	141.9	437
840-1799.9	29	4.61	7827	1224.0	267.4	355
1800-3719.9	45	3.26	4016	2532.0	498.3	200
3720+	20	0.73	884	5063.0	1283.0	51
TOTAL	125	24.0	44405	818.4	1061.0	1926

Notes:

- 1) Applies only to those miners whose total lifetime exposure is within indicated category.
- 2) Data were derived from USPHS data for white miners with underground uranium experience only (i.e. no other hard rock mining experience) and mortality experience to 31 December 1982.

in this Appendix, and with the exception of certain applications to subgroups of the Colorado Plateau miners, the regression technique described herein is applied to the whole group of miners. This is a limitation of the data available for this study. Where detailed data are available the technique can be applied to subgroups of miners such as those that might be classified by age, WLM exposure, and time since exposure, for example.)

When the left hand sides of (H.1) and (H.2) are plotted against $\bar{x}$, straight lines result which have intercepts α_1 , and β_1 , and slopes α_2 and β_2 . It is an important problem to use the available data to obtain estimates of these coefficients which are as good as possible. Of particular interest are estimates of the slopes, which in fact are the risk coefficients.

It is useful to obtain the best possible estimates of these coefficients in the form of a single value for each coefficient. It is essential, however, that some means be exploited to assess how close these estimates are likely to be to the corresponding true values. Thus the problem is addressed here of finding both point and interval estimates for the coefficients, which in statistical terminology are called parameters.

H.2 Fitting a Straight Line by Least Squares

In most cases where straight lines are fitted to data the Method of Least Squares is used. In it the values of the slope and intercept are adjusted until the sum of squares of vertical distances between the observed data and the postulated line are minimized as illustrated in Figure H.1. The values of slope and intercept which achieve this minimization are taken as the best estimates of their true values. Straightforward methods are available to establish limits between which the true values are expected to lie at a stated confidence levels.

In order to justify the Method of Least squares, it is necessary to make certain assumptions, as described below:

- (a) In fitting a straight, line each observation must be perfectly described by the mathematical model:

$$y_i = \theta_1^* + \theta_2^* x_i + \epsilon_i ; i = 1, 2, \dots, n \quad (\text{H.3})$$

where θ_1^* and θ_2^* are the true values (in the real world always more or less unknown to the observer) of the intercept and slope, x_i and y_i are the observed coordinates of the i th among n data points, and ϵ_i is an "error" which represents all the imperfection or lack of knowledge of the exact values of y_i and of the functional form of the true relationship. The asterisks are shown on the parameters θ_1 and θ_2 to emphasize that the model uses their true values.

- (b) It is assumed that the observations on the x_i perfectly represent the true values; i.e. the x_i are known without error. This assumption is a very important one, especially since it is simply not true in many scientific applications of the Method of Least Squares. It is difficult to judge how serious this in a particular case; sometimes the effect is negligible, but it can be very serious indeed.
- (c) It is assumed that the expected value (the long-term average value) of each ϵ_i is zero. In "ordinary" least squares, it is also assumed that the variance of ϵ_i , though possibly unknown, is the same for each i and that there are no correlations between ϵ_i and ϵ_j for $i \neq j$. If correlation or non-constant variance is present in a known form it is possible to accommodate it by the use of weighted least squares.
- (d) No assumption about the form of the distribution of the ϵ_i is required if the Method of Least Squares is only used to provide point estimates $\hat{\theta}_1$ and $\hat{\theta}_2$ for the parameters. In this case, it is shown (Draper and Smith, 1987, p. 87) that of all possible pairs of linear combinations of the data which have, on repeated sampling, the expectations θ_1^* and θ_2^* , the least squares estimates $\hat{\theta}_1$ and $\hat{\theta}_2$ have the smallest variances.

If confidence intervals for the parameters are to be calculated, it is necessary to make some assumption as to the form of the distributions of the ϵ_i . This is almost always that it is normal. It is only rarely a critical assumption because with reasonable amounts of data, $\hat{\theta}_1$ and $\hat{\theta}_2$ are usually almost normally distributed even if the ϵ_i are not.

If the assumption of normal distribution of the ϵ_i can reasonably be made, a further justification for the least squares estimates applies. It is

FIGURE H.1
 SKETCH ILLUSTRATING GEOMETRY OF LEAST SQUARES

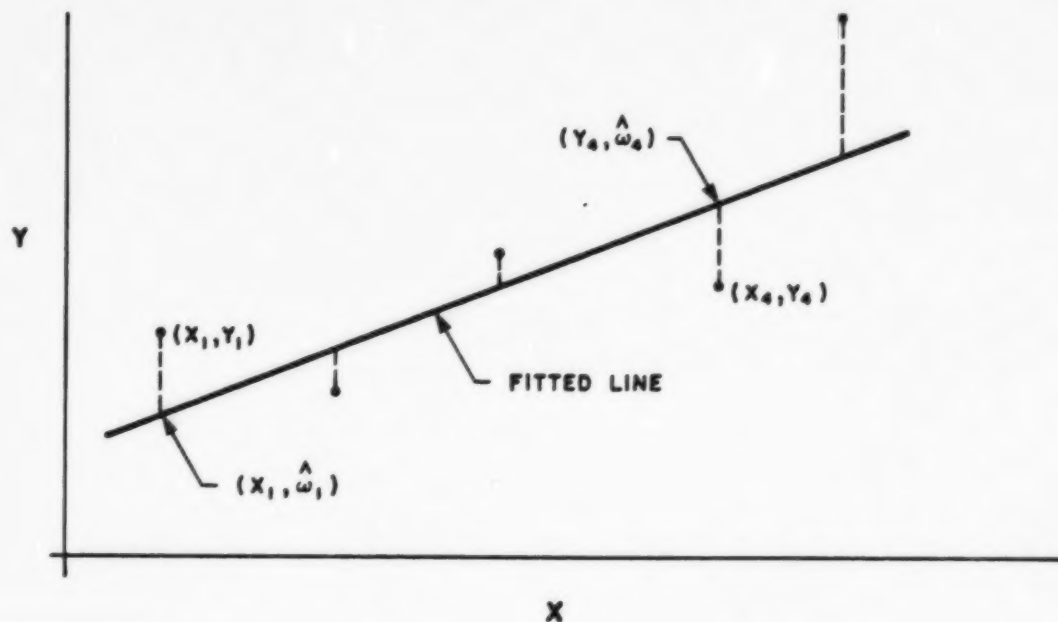
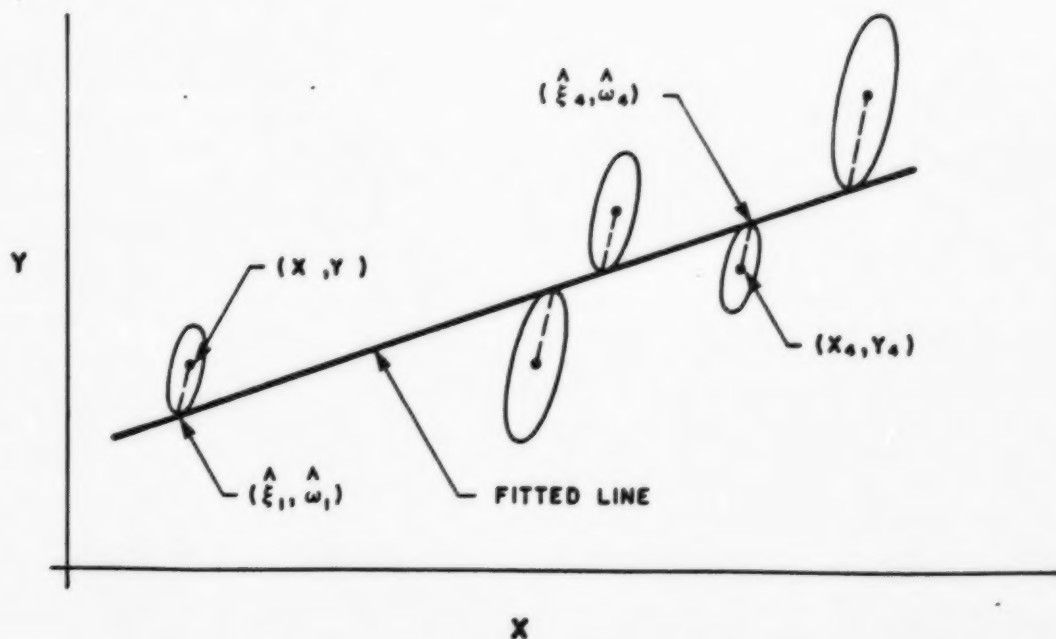


FIGURE H.2
 SKETCH ILLUSTRATING GEOMETRY OF EVM





that they are maximum likelihood estimates (Edwards, 1972; p. 203-204) in this case. This considerably broadens the justification for the method.

The utility of the Method of Least Squares to estimate the parameters in any particular problem depends critically on the applicability of the above assumptions. In examining the assumptions as applied to (H.1) and (H.2) it is immediately clear that the midpoint values of the exposure classes do not necessarily represent the average intensity of exposure and therefore, assumption (b). does not apply. Because this assumption frequently does not apply in problems of parameter estimation, there is a large literature on the subject. The most useful part of the literature for the current problem deals with the Error in Variables Model, which is discussed in the next section.

H.3 The Error in Variables Model (EVM)

When assumption (b) does not apply, i.e. when there is perceptible uncertainty in determining the x_i , the problem of fitting a straight line may be conveniently stated as follows: The observations x_i , y_i may be described by:

$$\left. \begin{aligned} x_i &= \xi_i^* + \epsilon_i \\ y_i &= w_i^* + \nu_i \end{aligned} \right\} \quad i = 1, 2, \dots, n \quad (\text{H.4})$$

where ξ_i^* and w_i^* are the true values of the measured quantities x_i and y_i . These are related to the true parameter values by:

$$w_i^* = \theta_1^* + \theta_2^* \xi_i^* ; \quad i = 1, 2, \dots, n \quad (\text{H.5})$$

The errors ϵ_i and ν_i , $i = 1, 2, \dots, n$ are usually assumed to be normally distributed with zero means and with known variances and covariance for each i . The errors for different i are assumed statistically independent and usually, though not necessarily, have the same variances and covariance.

It is desired to find parameter estimates of the parameters θ_1^* and θ_2^* given the model (H.4) and (H.5).

Reilly and Patino-Leal (1981) have studied a general form of this problem from the Bayesian point of view. They have produced the equivalent of a joint posterior probability density function for θ_1^* and θ_2^* and all the ξ_i^*

and w_i^* , $i = 1, 2, \dots, n$. From this they integrate out the ξ_i and w_i to produce a posterior probability density function for θ_1^* and θ_2^* . They show that for a given θ_1 and θ_2 , this probability density may be found as illustrated in Figure H.2 by first drawing the line using θ_1 and θ_2 as given and then for each i finding the point of tangency $(\hat{\xi}_i, \hat{w}_i)$ of the appropriate contour of constant probability content for ξ_i^* and w_i^* , given x_i and y_i . These contours form the ellipses shown in Figure H.2. For each i , there is a family of such ellipses with centre at (x_i, y_i) and with orientation established by the variances and covariance between ϵ_i and ν_i as in (H.4). The probability density for the given θ_1 and θ_2 is proportional to the sum over all the i of a measure of the sizes of the tangent ellipses. The calculation of the measure of size uses the quantities $\hat{\xi}_i$ and $\hat{w}_i$.

A point estimate $\hat{\theta}_1, \hat{\theta}_2$ may be obtained for the parameters by finding the mode or mean of this probability density function for θ_1^* and θ_2^* . Hence, the best straight line may be taken to be that which minimizes the sum of the sizes of the tangent ellipses centred on the observed points as shown in Figure H.2. This is analogous to the Method of Least Squares in which the best straight line is that one which minimizes the sum of squares of vertical distances to the measured points. In fact the analogy is closer yet; the size the i th ellipse may be measured as the square of the distance between the points (x_i, y_i) and $(\hat{\xi}_i, \hat{w}_i)$. When the error structure is the same for each i as is being assumed here, the lines joining these points for different i are parallel. Thus it may be said that the best straight line under EVM is found by choosing $\hat{\theta}_1$ and $\hat{\theta}_2$ so as to minimize the sum of squares of directed distances between the measured values and the fitted line, the direction being determined by the variances of the ϵ_i and ν_i and the covariance between them.

In the simple case of a straight line, a closed form solution is available for the point estimates $\hat{\theta}_1$ and $\hat{\theta}_2$ (Davies and Goldsmith, 1976, p. 209).

Reilly and Patino-Leal (1981) assume that the errors ϵ_i and ν_i are normally distributed with mean zero and known variances and covariance. It is this assumption which justifies the elliptical shape of contours of constant probability density in Figure H.2. The literature says little about the estimation of θ_1^* and θ_2^* when the errors are not normally distributed.

H.4 The Observed Number of Cases

In both (H.1) and (H.2) the quantity O , the observed number of cases is the only random variable appearing on the left hand sides. All other quantities are assumed to be perfectly known constants.

The number of lung cancers appearing in a defined group in a stated time period can be considered to be the result of a Poisson process, as described for example by Feller (1968, p. 446). As a result, the probability of observing a number of cases r is given by the Poisson formula.

$$Pr(O = r) = \frac{e^{-\lambda} \lambda^r}{r!} ; r = 0, 1, 2, \dots \quad (\text{H.6})$$

where r is an arbitrarily chosen non-negative integer, λ is the expected or long term average number of occurrences under the conditions considered and e is the base of natural logarithms.

It is known that when λ is large, say greater than 40, the shape of the distribution of O , except that it is discrete, is very close to normal. However, with small O it is far from normal. Since in Table H.1, no expected number of cases is as great as 6, normality cannot reasonably be assumed. (This is a common situation.)

As they stand, the left hand sides of (H.1) and (H.2) are not Poisson distributed; they are linear functions of a Poisson distributed quantity. In order to conform to a theory of EVM with a Poisson distributed variable it is necessary to rearrange (H.1) and (H.2) into the forms:

$$O = E + \alpha_1 PYR \times 10^{-6} + \alpha_2 PYR \times 10^{-6} \bar{x} \quad (\text{H.7})$$

and

$$O = E + \beta_1 \frac{E}{100} + \beta_2 \frac{E}{100} \bar{x} \quad (\text{H.8})$$

in which now the left hand sides are strictly Poisson distributed.

H.5 EVM with a Poisson Distributed Variable

Both (H.7) and (H.8) conform to a statistical model which has the functional relationship:

$$\lambda_i^* = u_i + \theta_1^* v_i + \theta_2^* w_i \xi_i^* ; i = 1, 2, \dots, n \quad (\text{H.9})$$

in which the observed variable O_i is Poisson distributed as in (H.6) with unknown mean λ_i^* ; and the observed variables x_i , $i = 1, 2, \dots, n$ are described as in (H.4) as normally distributed with unknown means ξ_i^* , $i = 1, 2, \dots, n$ and known variances σ_i^2 , $i = 1, 2, \dots, n$. The quantities u_i , v_i and w_i are perfectly known constants while θ_1^* and θ_2^* represent the parameters of (H.1) and (H.2), all of which are interpreted in terms of (H.7) and (H.8) in Table H.2. All observed variables in the i th group are independent of each other and of the observed variables in the j th group for $i, j = 1, 2, \dots, n$, $i \neq j$.

Using the prior suggested by Lindley (1965, p. 155), the posterior probability density function for λ_i^* is:

$$Df(\lambda_i^* | O_i) = \frac{e^{-\lambda_i^*} \lambda_i^{O_i-1}}{(O_i - 1)!} \quad i = 1, 2, \dots, n \quad (\text{H.10})$$

Similarly, using a uniform prior for ξ_i^* , the posterior probability density function for exposure ξ_i^* is as given by Lindley (1965, p. 19):

$$Df(\xi_i^* | \bar{x}_i) = \frac{1}{\sigma_i \sqrt{2\pi}} \exp \left\{ -\frac{1}{2} \left(\frac{\xi_i^* - \bar{x}_i}{\sigma_i} \right)^2 \right\} \quad (\text{H.11})$$

Since O_i and x_i are statistically independent, a contour of joint posterior probability for λ_i^* and ξ_i^* is described by equating the product of the right hand sides of (H.10) and (H.11) to a constant. To find the contour which is tangent to (H.9) for a given θ_1 and θ_2 , similar to the contours shown in Figure H.2, the same product should be minimized with respect to λ_i and ξ_i subject to (H.9). This can be accomplished through the use of the Lagrangian:

Table H.2: Interpretation of Poisson EVM Notation

Symbol in Poisson EVM Model (H.9)	Meaning in Absolute Risk model, (H.1) and (H.7)	Meaning in Relative Risk Model, (H.2) and (H.8)
O_i	O_i	O_i
u_i	E_i	E_i
v_i	$10^6 PY R_i$	$.01 E_i$
w_i	$10^6 PY R_i$	$.01 E_i$
x_i	$\bar{x}_i$	$\bar{x}_i$
θ_1	α_1	β_1
θ_2	α_2	β_2
λ_i	$E(O_i)$	$E(O_i)$
ξ_i	$E(\bar{x}_i)$	$E(\bar{x}_i)$
σ_i^2	$Var(\bar{x}_i)$	$Var(\bar{x}_i)$

Notes:

- 1) In the above E_i is the expected number of cases for the i th group of miners as described for (H1) and (H2) while E is the expectation operator as used in the statistical literature.
- 2) $Var(\bar{x}_i)$ is the square of "Standard Deviation of Exposure" in Table H.1.
- 3) The symbol E_i refers to the expected number of cases in the i th group of miners; E is an algebraic operator which represents the taking of expectations.



$$L(\lambda_i, \xi_i) = \lambda_i - (O_i - 1) \ln \lambda_i + \frac{1}{2} \left(\frac{\xi_i - x_i}{\sigma_i} \right)^2 + \gamma_i (u_i + \theta_1 v_i + \theta_2 w_i \xi_i - \lambda_i) \quad (\text{H.12})$$

The function L was obtained by discarding quantities independent of λ_i and ξ_i from the right hand sides of (H.10) and (H.11) and then adding their negative logarithms. To this sum was added the product of the Lagrange multiplier γ_i and the right hand side of (H.9) after transferring λ_i . Then (H.12) is differentiated with respect to λ_i and ξ_i and the derivatives equated to zero to yield two equations in the three unknowns λ_i , ξ_i and γ_i .

A third equation is provided by (H.9). The solutions $\hat{\lambda}_i$ and $\hat{\xi}_i$ are the estimated true values of O_i and x_i . The solution for ξ_i is given by:

$$\hat{\xi}_i = \frac{1}{2\theta_2 w_i} \left\{ \left([u_i + \theta_1 v_i + \theta_2 w_i (x_i - \theta_2 \sigma_i^2 w_i)]^2 + 4\theta_2^2 w_i^2 \sigma_i^2 [O_i - 1] \right)^{\frac{1}{2}} - u_i - \theta_1 v_i + \theta_2 w_i (x_i - \theta_2 \sigma_i^2 w_i) \right\} \quad (\text{H.13})$$

Then $\hat{\lambda}_i$ is found by substituting $\hat{\xi}_i$ from (H.13) into (H.9).

The likelihood function for θ_1^* and θ_2^* function is found by substituting each $\hat{\xi}_i$ and $\hat{\lambda}_i$ into (H.10) and (H.11) and multiplying them all together to get:

$$L(\theta_1, \theta_2 | O_i, x_i, i = 1, 2, \dots, n) \propto \prod_{i=1}^n \hat{\lambda}_i^{O_i-1} \exp \left\{ -\hat{\lambda}_i - \frac{1}{2} \left(\frac{\hat{\xi}_i - x_i}{\sigma_i} \right)^2 \right\} \quad (\text{H.14})$$

Quantities whose values do not depend on θ_1 or θ_2 and which appear as multipliers have been dropped.

H.6 Summary of Procedure to Find the Joint Likelihood Function for θ_1 and θ_2

1. Using Table H.2, identify the symbols in (H.9) in terms of the data and the model being used.

2. Choose an arbitrary pair of values for θ_1 , and θ_2 .
3. For each i , calculate $\hat{\xi}_i$ using (H.13) and $\hat{\lambda}_i$ using (H.9).
4. Substitute the $\hat{\xi}_i$ and $\hat{\lambda}_i$ along with x_i and O_i for all $i = 1, 2, \dots, n$ into (H.14) to obtain a likelihood for the θ_1 , and θ_2 in 2.
5. Repeat 2,3, and 4 as required for the values of θ_1 , and θ_2 desired.

H.7 Preparing and Using the Joint Posterior Probability Density Function

The joint posterior probability density function for θ_1 and θ_2 may be obtained through the use of Bayes' Theorem by multiplying the likelihood in H.14 by an appropriate prior.

A convenient way in which to organize the relatively awkward calculations in this is by the method described Reilly (1981). As applied to this problem, a matrix is set up in computer memory, the i, j element of which corresponds to a particular pair of values for θ_1 and θ_2 according to the scheme:

$$\begin{aligned}\theta_1 &= a_1 + b_1 i \\ \theta_2 &= a_2 + b_2 j\end{aligned}\tag{H.15}$$

where the a 's and b 's are constants chosen so as to produce useful values of θ_1 and θ_2 . The number stored in the i, j element of the matrix is the joint probability of the corresponding θ_1 and θ_2 .

Initially, the probability in each element is the same, expressing no prior knowledge about the parameter. When some data are available, the probability in each element of the matrix is multiplied by the likelihood calculated as described in Section H.6, using for each element the corresponding values of θ_1 and θ_2 . The standardized probabilities are then obtained by dividing the number in each element by the sum of all of them.

At first the correct ranges for θ_1 and θ_2 will not be known. This will be indicated by large probabilities at one or more of the edges of the matrix. At this stage it is desirable to use a small, say 11 by 11, matrix and by trial and error adjust the constants in (H.15) until most of the probability is near the centre of the matrix and very little on the edges. Then using the

Table H.3: 11 × 11 Trial Matrix for Absolute Risk Model, (% Probabilities)

$$\left. \begin{aligned} \alpha_1 &= -783 + 83I \\ \alpha_2 &= 2.03 + 0.27J \end{aligned} \right\} \text{ for } I, J \text{ element} \quad (\text{H.1})$$

[illegible]

Table H.4: 11 × 11 Trial Matrix for Relative Risk Model, (% Probabilities)

$$\left. \begin{aligned} \beta_1 &= -166 + 26I \\ \beta_2 &= 0.195 + 0.0055J \end{aligned} \right\} \text{ for } I, J \text{ element} \quad (\text{H.1})$$

 β_2 [illegible]

same ranges for θ_1 and θ_2 but a larger matrix, say 101 by 101, the final joint probability density function may be obtained. Using this, marginal probability density functions, mean and modal values, and probability density functions for the parameters are easily examined.

H.8 Examples

The data in Table H.1 are used to illustrate the method.

Tables H.3 and H.4 show for the absolute and relative risk models, the 11×11 matrices which resulted from the trial and error procedure to establish the ranges for the parameters. The values of the constants in (H.15) are also shown.

Figure H.3 shows the marginal probability distribution for α_2^* , the slope in the absolute risk model shown in (H.1). It was obtained as the column sums in the matrix.

The straight line in Figure H.4 is the mean line for the absolute risk model. Its intercept was found by summing $\alpha_1 Pr(\alpha_1, \alpha_2)$ over all elements of the matrix. The slope was found by summing $\alpha_2 Pr(\alpha_1, \alpha_2)$ over the matrix.

The probability distributions in Figure H.4 above $x = 0$, $x = 2500$ and $x = 5000$ express the posterior uncertainty in the position of the true relationship between risk and exposure. For the distribution for a particular value of x a system of cells or bins was established with cell width 500 on the vertical scale of the graph. Then for each element of the matrix, its probability was added into the cell corresponding to $\alpha_1 + \alpha_2 x$.

Figure H.5 shows the marginal distribution of the slope β_2^* for the relative risk model. Figure H.6 shows the graph of the straight line relationship for that model.

In Figures H.3, H.4, H.5 and H.6 probability distributions are obtained by plotting sums of probabilities from the 101 by 101 matrix obtained as described in the last section. The smooth curves are drawn through these plotted points, though the points invariably confirm closely to the curves. These curves are to be interpreted as probability density functions, though the vertical scales must be multiplied by a scale factor in each case to make the areas under the probability density functions equal to 1.

H.9 References

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FIGURE H.3
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (α)
 ABSOLUTE RISK MODEL, U.S. URANIUM MINERS ONLY
 (SEE TABLE 4.2)

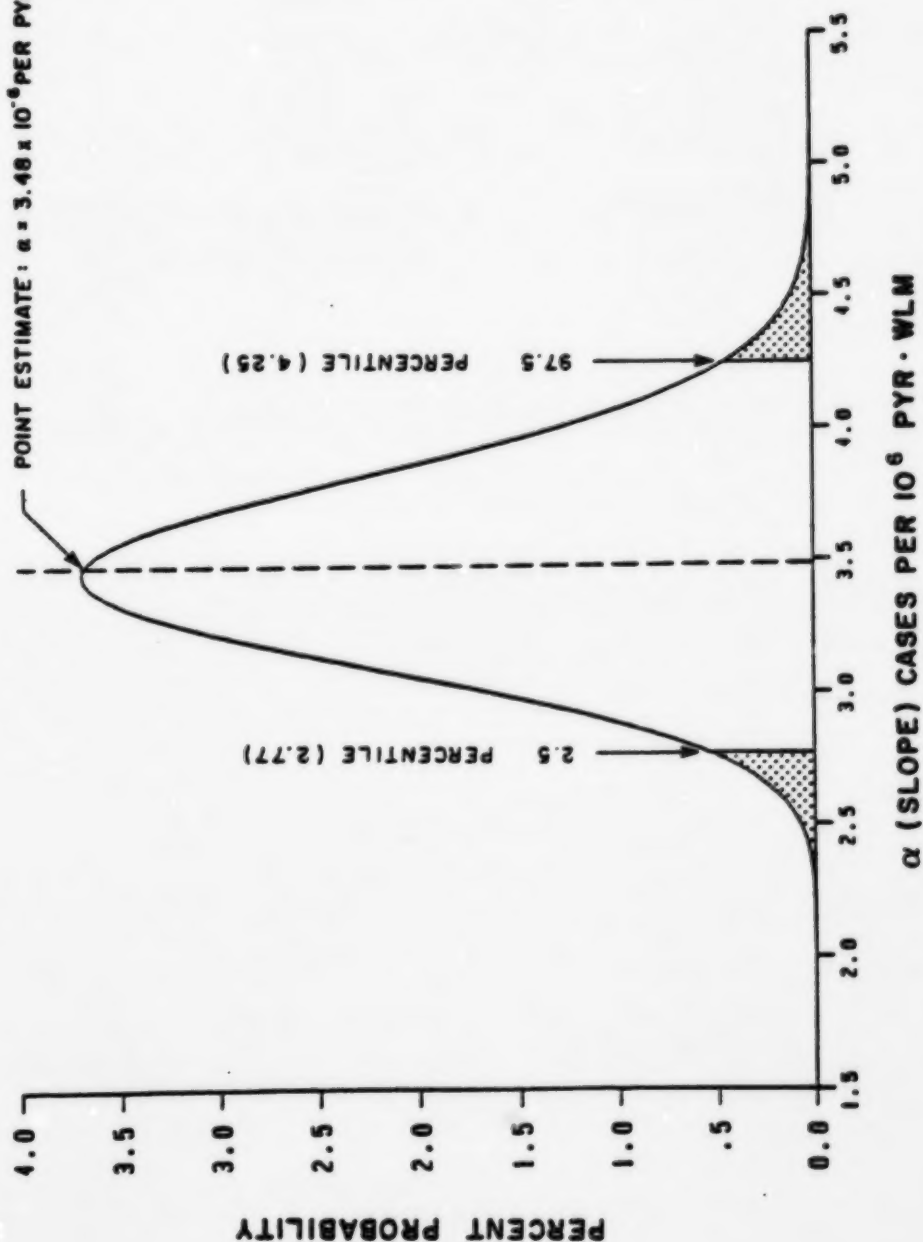


FIGURE H.4
INCIDENCE OF LUNG CANCER FOR U.S. URANIUM MINERS ONLY
ABSOLUTE RISK MODEL
(SEE TABLE 4.2)

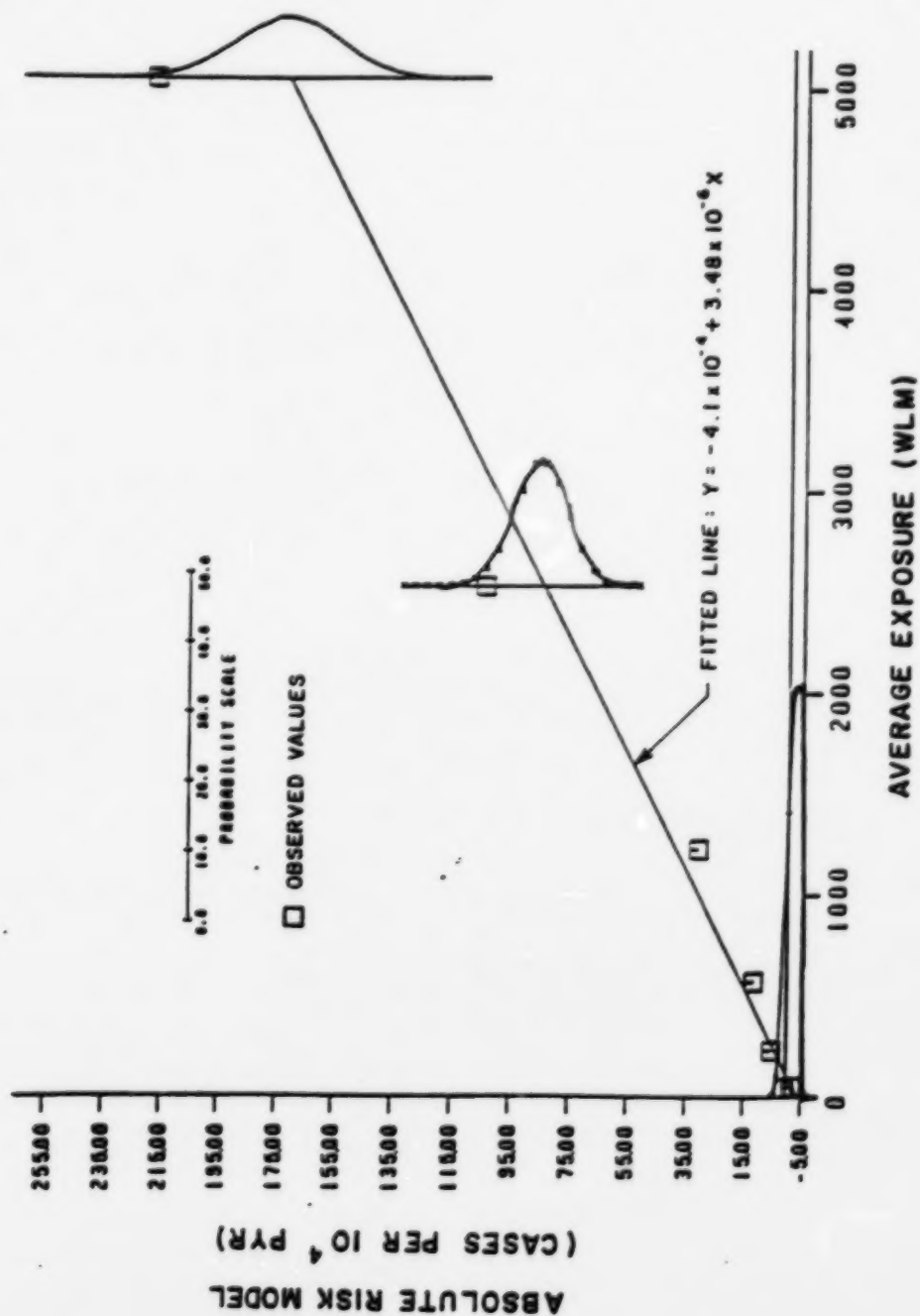


FIGURE H.5
 MARGINAL PROBABILITY DISTRIBUTION FOR SLOPE (β)
 RELATIVE RISK MODEL, U.S. URANIUM MINERS ONLY
 (SEE TABLE 4.2)

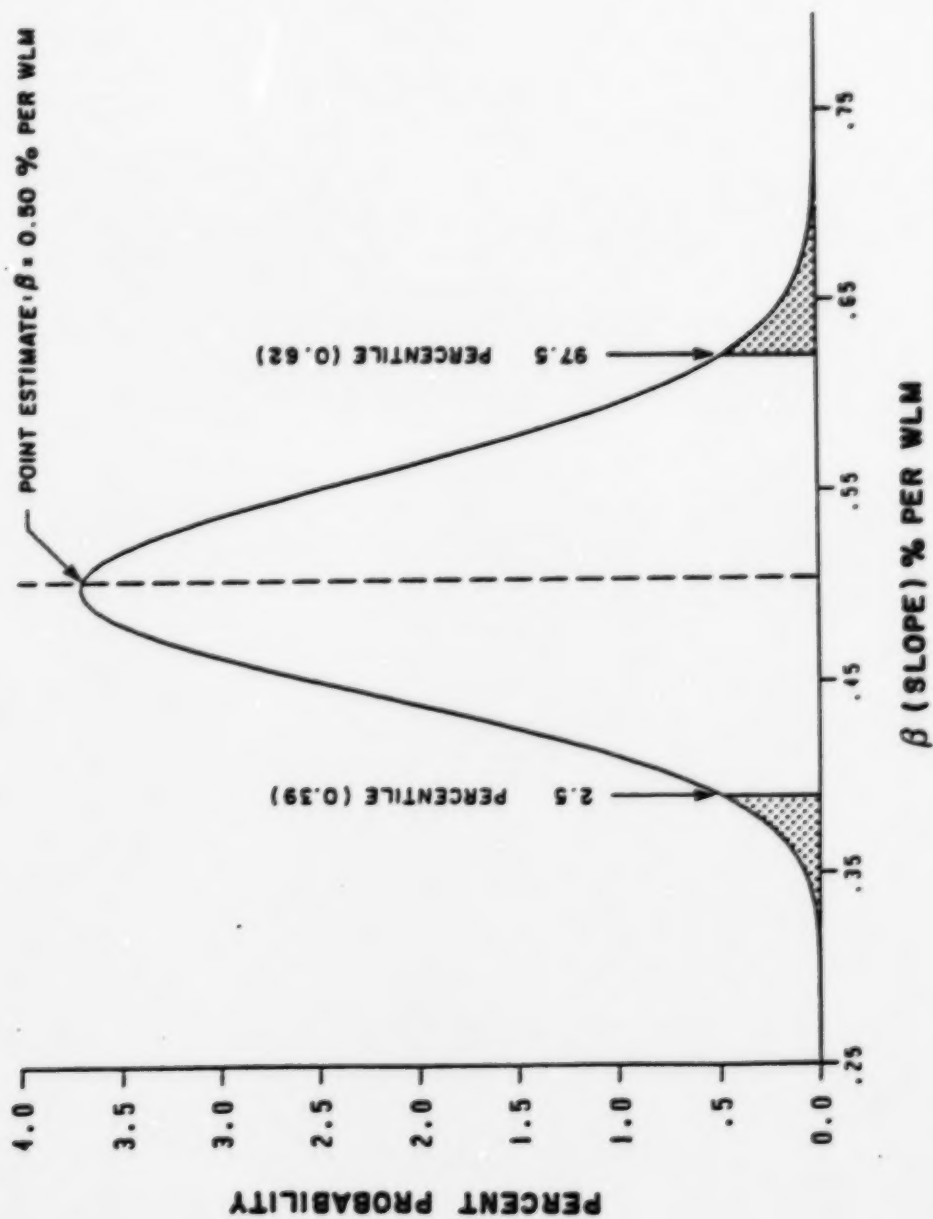
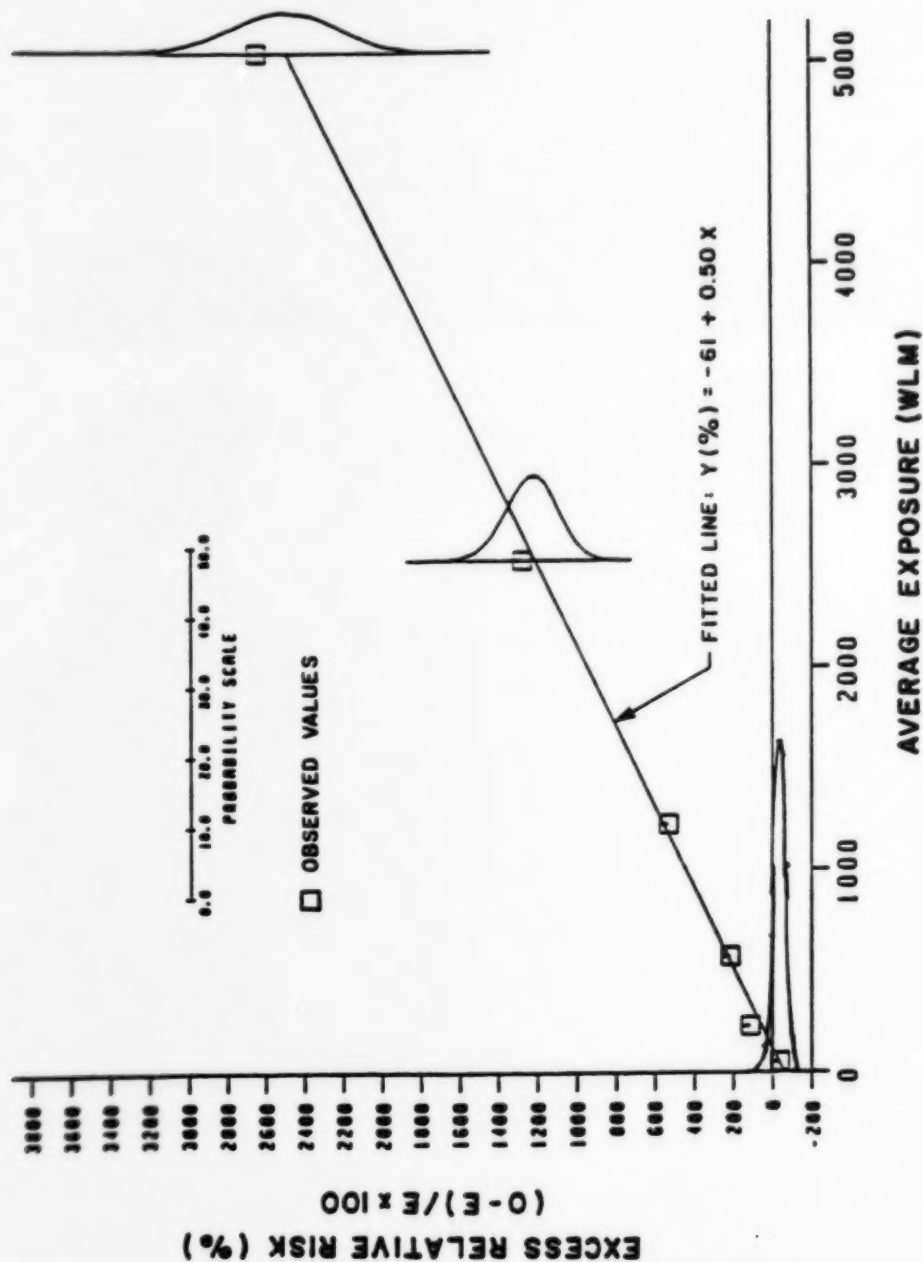


FIGURE H.6
INCIDENCE OF LUNG CANCER FOR U.S. URANIUM MINERS ONLY
RELATIVE RISK MODEL
(SEE TABLE 4.2)



Appendix I

The Effect of Uncertainty in WLM Exposure on Rate of Lung Cancer in Uranium Miners – An Application of Bayesian Methods

I.1 Introduction

A major problem in all of the epidemiological studies of miners exposed to radon daughters is the reliability of the (WLM) exposure estimates. Typically, radon daughter measurements were infrequent or absent during the earliest years of mining. As time advances, the basis for estimating the exposure of miners to radon daughters improves. However, even nowadays exposure estimation is not an exact science and some uncertainty remains about a miner's day to day or year to year exposure.

In this appendix we describe an approach, based on Bayesian methods, to evaluate the effect of uncertainty about the miner's cumulative WLM exposure on the risk coefficient derived from any epidemiological study. The technique requires only an estimate of the cumulative WLM exposure of the entire study group and an estimate of the numbers of lung cancers (potentially) attributable to that exposure. Such data are readily available from most published studies. The technique allows the investigator to make different assumptions about the characteristics of the uncertainty associated with the cumulative WLM exposure. The method assumes the relation between attributable risk and increasing WLM exposure to be linear.

I.2 Concepts

If a specified group of miners over a specified time period have an expected (long term average on repeating the experience) number of lung cancers λ , the observed number K on a single occasion can realistically be considered to result from a Poisson process (Feller, 1968, Vol. 1, 3rd ed., p. 446). The probability distribution for K is then given by:

$$p(k) = \text{Pr}(K = k) = \frac{\lambda^k e^{-\lambda}}{k!}, k = 0, 1, 2, \dots \quad (\text{I.1})$$

If under similar conditions, k lung cancers have been observed, the posterior probability density for λ may be written, using Bayes' theorem, as:

$$Df(\lambda|k) \propto \pi(\lambda) \lambda^k e^{-k}; 0 < \lambda < \infty \quad (\text{I.2})$$

in which $\pi(\lambda)$ is the prior distribution for λ .

There are three possibilities for π which are most commonly used, all of which are of the form λ^{-a} . Bayes' postulate prescribes $a = 0$, resulting in a uniform prior for λ . This is in the spirit of Box and Tiao (1973, p. 48) and it seems reasonable as a local approximation if λ is assumed large. In fact Box and Tiao (1973, p. 40) recommend $a = \frac{1}{2}$, while (Lindley, 1965, Vol. 2, p. 155) recommends $a = 1$. In both of these last two cases π is essentially uniform if the likelihood is only perceptible for large λ .

Assuming $a = 0$, we may standardize (1.2) to get the gamma distribution:

$$Df(\lambda|k) = f(\lambda) = \frac{\lambda^k e^{-\lambda}}{k!} \quad \lambda > 0, k \text{ integer} \quad (1.3)$$

Note the mathematical coincidence that supplying the standardizing constant makes $f(\lambda)$ in (1.3) identical to $p(k)$ in (1.1). However, p sums to 1 over k while f integrates to 1 over λ .

Suppose now we postulate that $\lambda = \bar{\lambda}W$ where $\bar{\lambda}$ is the attributable risk of lung cancer per WLM of aggregate exposure in the group, and W is the aggregate exposure in WLM. For a fixed and known W we may transform (1.3) to obtain the posterior distribution of $\bar{\lambda}$, i.e.

$$Df(\bar{\lambda}|k, W) = \frac{W^{k+1}}{k!} \bar{\lambda}^k e^{-\bar{\lambda}W} \quad W > 0 \quad (1.4)$$

The assumption of uniform prior for λ still applies in (1.4). If W is not known perfectly, but is a random variable with known probability distribution $Df(w)$ we may write:

$$Df(\bar{\lambda}|k) = \int_w Df(\bar{\lambda}|k, W) Df(W) dW \quad (1.5)$$

I.3 Application

In the present analysis we have developed relation (1.5) for 3 different distributions of W , namely uniform, triangular and normal.

Case 1: W Uniformly Distributed

If W has the uniform distribution $U(a, b)$, (1.4) and (1.5) lead to:

$$Df(\bar{\lambda}|k) = \frac{\bar{\lambda}^k}{k!(b-a)} \int_a^b W^{k+1} e^{-\bar{\lambda}W} dW \quad (I.6)$$

which may be simplified to

$$Df(\bar{\lambda}|k) = [k!(b-a)\bar{\lambda}^2]^{-1} \int_{a\bar{\lambda}}^{b\bar{\lambda}} v^{k+1} e^{-v} dv \quad (I.7)$$

The integral in (I.7) may be expressed as an incomplete gamma integral, which may be reduced to a χ^2 integral. From (Abramowitz and Stegun, 1965, pp. 260 and 291):

$$\gamma(a, x) = \int_0^x v^{a-1} e^{-v} dv = \Gamma(a) Pr \{ \chi_{2a}^2 \leq 2x \} \quad (I.8)$$

where $\gamma(a, x)$ is the incomplete gamma function, and $\Gamma(a)$ is the gamma function:

$$\Gamma(a) = \int_0^\infty v^{a-1} e^{-v} dv \quad (I.9)$$

i.e. $\Gamma(a) = \gamma(a, \infty)$. If a is a positive integer $\Gamma(a) = (a-1)!$. χ_p^2 is the χ^2 distribution with p degrees of freedom. Note that (I.8) is exact. Using (I.7) and (I.8):

$$Df(\bar{\lambda}|k) = \frac{k+1}{(b-a)\bar{\lambda}^2} [Pr(\chi_{2k+4}^2 \leq 2b\bar{\lambda}) - Pr(\chi_{2k+4}^2 \leq 2a\bar{\lambda})] \quad (I.10)$$

Since the χ^2 quantities have large degrees of freedom, they may be approximated by normally distributed quantities. Using an approximation from (Abramowitz and Stegun, 1965, p. 941).

$$Pr(\chi_v^2 \leq K) \simeq Pr \left[Z \leq \frac{\left(\frac{K}{v}\right)^{\frac{1}{2}} + \frac{2}{9v} - 1}{\sqrt{\frac{2}{9v}}} \right] \quad v > 30 \quad (I.11)$$

where Z is normally distributed with mean zero and variance 1, i.e.

$$Z: N(0, 1)$$

Standard tables and computer programs give the probability required in (I.11).

The approximation in (I.11) is said by Abramowitz and Stegun to be acceptable for $v > 30$, which is equivalent in (I.10) to $k > 13$. In the cases tested it was found very accurate.

Case 2: W Triangularly Distributed

Suppose W is triangularly distributed with minimum pW_0 , mode W_0 and maximum qW_0 , for $p < 1 < q$. Then:

$$\begin{aligned} Df(W) &= \frac{2}{W_0^2(q-p)(1-p)}(W - pW_0) & pW_0 \leq W \leq W_0 \\ &= \frac{2}{W_0^2(q-p)(q-1)}(qW_0 - W) & W_0 \leq W \leq qW_0 \\ &= 0 & \text{otherwise} \end{aligned} \quad (I.12)$$

Using this with (I.4) and (I.5) and a development similar to that for the uniformly distributed case, leads to the approximate formula:

$$\begin{aligned} Df(\bar{\lambda}|k) &\propto \\ &\frac{W_0}{\lambda^2} \left[\frac{p}{1-p} g(k+2, p\bar{\lambda}W_0) - \left(\frac{p}{1-p} + \frac{q}{q-1} \right) g(k+2, \bar{\lambda}W_0) \right. \\ &\quad \left. + \frac{q}{q-1} g(k+2, q\bar{\lambda}W_0) \right] \\ &- \frac{k+2}{\lambda^2} \left[\frac{1}{1-p} g(k+3, p\bar{\lambda}W_0) - \left(\frac{1}{1-p} + \frac{1}{q-1} \right) g(k+3, \bar{\lambda}W_0) \right. \\ &\quad \left. + \frac{1}{q-1} g(k+3, q\bar{\lambda}W_0) \right] \end{aligned} \quad (I.13)$$

where $g(a, x) = \Pr(\chi_{2a}^2 \leq 2x)$ as given by (I.11)

Case 3: W Normally Distributed

If W is distributed as $N(\mu, \sigma^2)$, (I.5) is equivalent to the statement that $Df(\bar{\lambda}|k)$ is the expectation of the right hand side of (I.4) under variation

in W with $W: N(\mu, \sigma^2)$. This is very easy to implement using Gaussian quadrature as:

$$E[f(W)] \simeq \frac{1}{\sqrt{\pi}} \sum_{i=1}^n w_i f(\mu + \sigma x_i \sqrt{2}) \quad (I.14)$$

where the x_i are the zeros of the n th degree Hermite polynomial, and w_i are the associated weights (Abramowitz and Stegun, 1965, p. 924). The approximation is better with higher n .

I.4 Examples

Example calculations are provided for the U.S. miners for which there are some $k = 259$ lung cancers potentially associated with an aggregate exposure of approximately 2.78×10^6 WLM. (In reality there are a total of 259 lung cancer cases observed in this population to 31 December, 1982. Some of these are due to natural causes, as well as possibly the effects of exposure to workplace agents other than radon daughters.)

Graphs are shown in Figure I.1 for the distribution of $\bar{\lambda}$ with both a uniform distribution and a triangular distribution for W . The mean value of $\bar{\lambda}$ is preserved for each distribution. In either situation, the analysis suggests that the most probable value of $\bar{\lambda}$, the expected risk per WLM of exposure is in the order of 100 cases per 10^6 WLM or less and is not likely (from this analysis) to exceed 150 cases per 10^6 WLM or so.

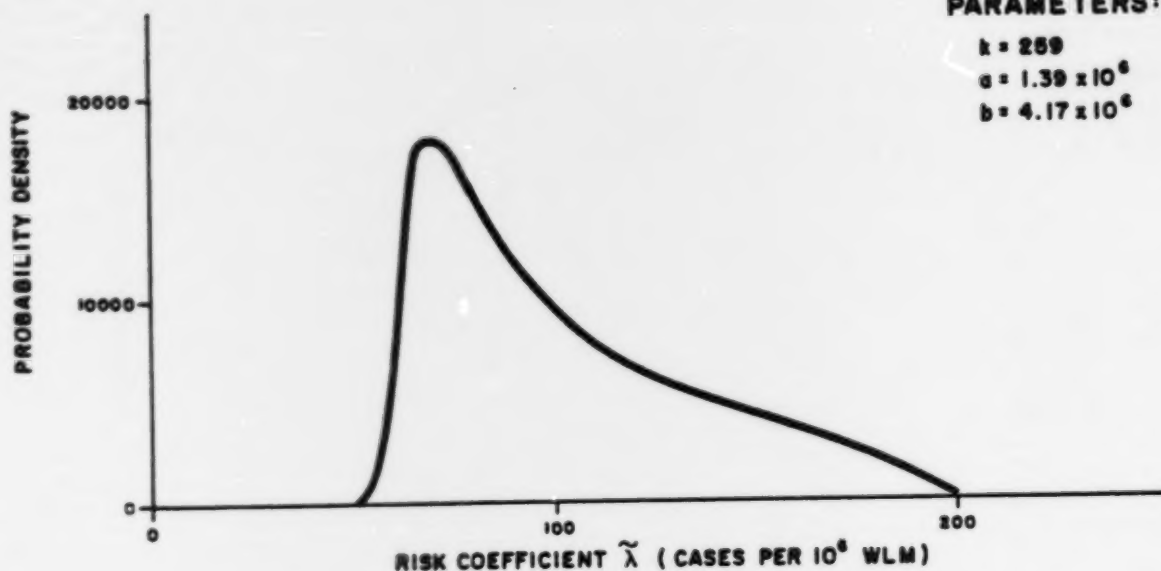
The normal distribution was not used in this particular illustration because normal distributions of the order of width used in the uniform and triangular cases, when substituted into (I.14), required evaluation of (I.4) for negative W which is not within the domain of the function.

FIGURE I.1

POSTERIOR DISTRIBUTION OF RISK COEFFICIENT $\tilde{\lambda}$ [$Df(\tilde{\lambda}|k)$]

PARAMETERS:

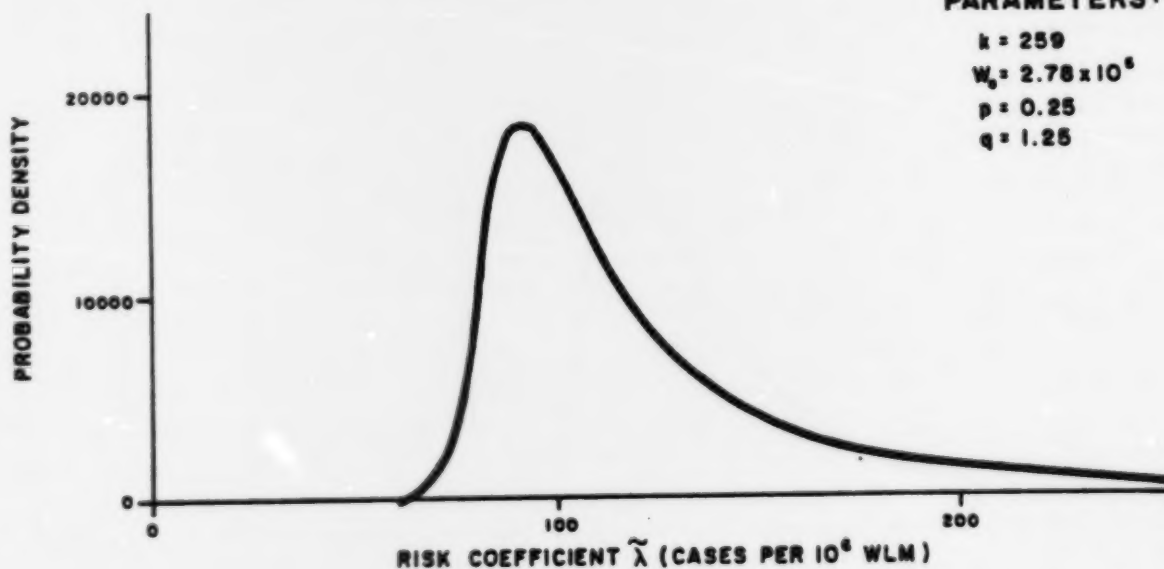
$k = 259$
 $a = 1.39 \times 10^6$
 $b = 4.17 \times 10^6$



A) UNIFORM DISTRIBUTION FOR W

PARAMETERS:

$k = 259$
 $W_0 = 2.78 \times 10^6$
 $p = 0.25$
 $q = 1.25$



B) TRIANGULAR DISTRIBUTION FOR W

NOTE:

1. THE ABOVE GRAPHS HAVE IDENTICAL HORIZONTAL AND VERTICAL SCALES AND ARE EACH STANDARDIZED SO AS TO INTEGRATE TO 1.

I.5 References

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